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Final Report

COMPACT COHERENT OPTICAL CORRELATOR SYSTEM

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A real-time coherent optical correlator was designed, fabricated and tested. The correlator features 30 separate filters, low-light level real-time operation, and a compact design. The correlator is packaged in a cylinder 15 cm in diameter by 30 cm long, excluding imaging lens. Each of the two laser diode coherent light sources is imaged to 15 locations with holographic optical elements (HOEs). The HOEs perform a number of functions usually requiring several optical components. The HOEs correct the aspect ratio of the laser diode beams, perform the functions of collimating and Fourier transform lenses, multiplex the light beam to form multiple Fourier transforms, and correct a variety of system aberrations.

Low-light operation is achieved with a microchannel image intensifier in front of a liquid crystal light modulator. This arrangement allows the correlator to

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operate over a wide range of light levels, from full sunlight to dusk. The image intensifier, however, reduces system resolution and response time.

A computer controlled filter maker system was designed to automate filter recording. The computer, a small PC-type, controls the position of the recording plate, the reference beam angle, dwell and exposure times, and checks light source and shutter operation.

PREFACE

This report was prepared by the Optical Science Laboratory, the Environmental Research Institute of Michigan, under contract No. DAAG011-85-C-1144 with the U.S. Army Missile Command, Redstone Arsenal, Alabama. This report describes work performed between September 1, 1985, and February 29, 1988. The effort was monitored by Dr. C.R. Christensen, AMSMI-RRO. The contractor's number for this report is 190200-51-F. The principal investigator was Juris Upatnieks. Mechanical design and fabrication was under the supervision of Perry Perrault, and electronic design and testing by Jim Abshier and Alex Klooster. Other staff members that participated in this project were J. Cederquist, A. Klooster, N. Subotic, A. Tai and N. Vlannes.

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1.0 INTRODUCTION

This report describes the design, fabrication and testing of a compact coherent optical correlator and a matched filter maker system. The correlator performs two-dimensional correlation of the input scene against images stored in the filters for the purpose of image recognition. The input scene enters the correlator via an imaging lens in real time while the filters are prerecorded on photographic plates that can be inserted into the correlator. In case of a match, a bright correlation spot appears at the output plane that is detected by a miniature television camera and is converted into a standard composite video signal. The spot position indicates the location of the object in the input scene. The output signal can be displayed and observed on any TV monitor or can be used as the input to other follow-on processors or control systems in fully automated applications.

The operating and performance requirements for the system were: 1) address 30 separate filter positions, 2) fit within a 15 cm diameter cylinder approximately 30 cm long, 3) operate over a 10^4:1 scene brightness range, corresponding to a range from bright sunlight to a dark, overcast sky, 4) operate in real time, 5) fabricate filters within a 30 minute time period. These requirements went well beyond what had been done previously and required the solution of a number of technical problems and innovative approaches. An image intensifier in conjunction with attenuators increased the brightness range over which the correlator operates. Specially fabricated holographic optical elements combined the functions of several standard optical elements reducing the correlator size. An ultraprecise plate holder was fabricated to precisely reposition prerecorded filters in the correlator.

Details of the correlator package are given in Section 2, of the filter maker system in Section 3, and design considerations and choices in Section 4. Fabrication of a specialized holographic optical element

essential to the correlator is described in Section 5. Component and system tests are covered in Section 6, future improvements in Section 7, and summary and recommendations are in Section 8. The appendices contain the filter maker computer program printout, custom-made electronic circuit diagrams used in the correlator, and a list of major or unique components.

2.0
COMPACT CORRELATOR

2.1 GENERAL DESCRIPTION

The correlator, shown in Fig. 2-1, is a compact package with all of the components, except for the imaging lens, packed into a cylinder 15cm in diameter and 30.5cm long. The imaging lens can be any standard Nikon-compatible 35mm camera lens. A power supply is provided as a seperate unit to convert 115V AC to $\pm$12 V and +5 DC necessary to operate the internal electronic components. Specifications of the correlator are listed in Table 2-1. Fig. 2-2 shows the major components mounted inside the correlator.

The correlator is designed to operate in real time over a wide range of light levels. The correlator "looks" at real world by imaging a real scene onto an image intensifier having a gain of about 1.5×10^4. The output of the intensifier is coupled through a fiber optics faceplate directly to a liquid crystal light valve (LCLV). On one side the LCLV modulates a coherent light beam according to the incoherent image intensity incident on the opposite side. The optical system takes the Fourier transform (FT) of the input scene and displays it at thirty separate locations, where appropriate matched filters are located. Matched filters are recorded on glass plates which are mounted on special steel frames and can be replaced with a high degree of accuracy.

A lens after the filter plane takes the inverse Fourier transform and displays the correlation spots on a solid state miniature TV camera. The output video signal can be displayed and observed on any TV monitor.

Coherent light is provided by a pair of 30mW laser diodes emitting at 780 nm wavelength. Due to the inherent wavelength drift of the diodes due to temperature changes, thermoelectric cooling is provided with a thermistor temperature sensor feedback. The diodes are

Figure 2-1. Compact correlator (left) and power supply.

Table 2-1
Correlator Specifications

Size:	15.3 cm diameter x 30.5 cm long
Weight (estimated):	15 lbs.

Number of filter positions:	30
Input:	direct imaging
Image brightness range (with attenuators):	dusk to full sunlight
Input image resolution:	8 lines/mm
Response time:	1 second
Internal laser diode light source:	
Power rating:	30 mw
Wavelength:	780 nm
Model:	Sharp LT024MF
Number of diodes:	2

Lens mount:	standard Nikon bayonet
Imaging lens:	35 to 200 mm focal length
Correlator output:	composite video signal
Power requirements:	+5V, 5 amp.
	$\pm$ 12V, 0.2 amp.

Power supply	
Input:	120V, 50 Hz
Controls:	Power On/Off
	Laser diode #1 On/Off
	Laser diode #2 On/Off

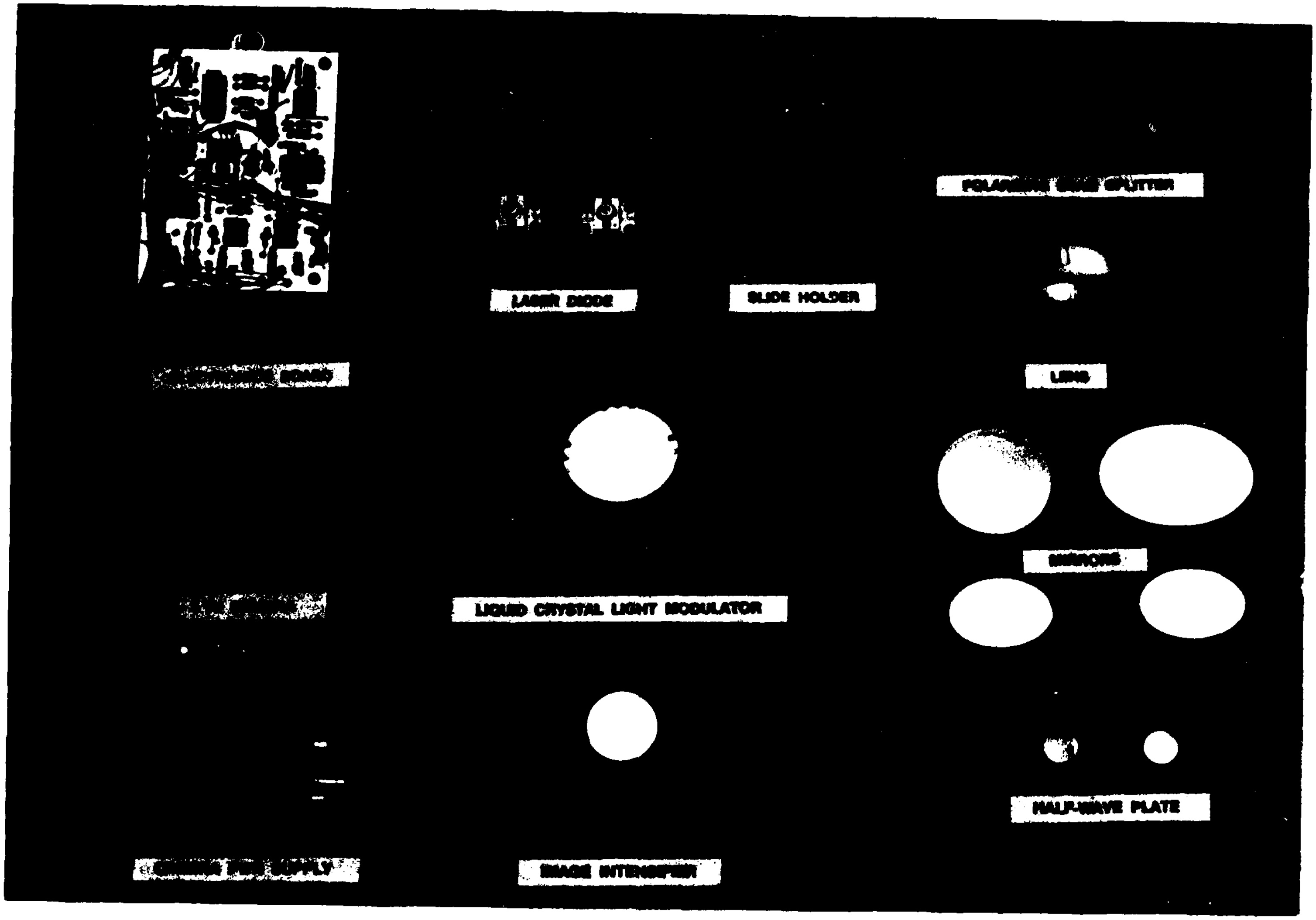


Figure 2-2. Major correlator components.

maintained at a constant operating temperature. The diodes contain a light sensor which provides feedback to laser diode output stabilization circuit. The two laser diodes operate at a constant temperature that insures wavelength stability and with light feedback that provides light output stability. The electronic circuits for laser diode control are located at the back of the correlator, as is an audio-frequency oscillator to provide bias for the LCLV. A voltage divider circuit is included to provide the 2.7 volts for the image intensifier.

In order to operate the correlator at low light levels, an image intensifier was used which unfortunatley reduced the correlator temporal response and resolution. The relatively low intensifier output brightness required a LCLV bias setting that reduced its response time to about one second as compared to 0.1 sec. at specified brightness. Also, if the lens cap has been on for some time so that the LCLV has not received any light, more than ten seconds are needed for the LCLV to reach normal operating level.

The resolution of the LCLV is about 30 l/mm, of the image intensifier about 18 l/mm, and of the combination about 8 l/mm. This reduced resolution is caused by the mismatch of fibers at the intensifier-LCLV interface.

When not actively in use, the lens cap should always cover the imaging lens. This is to prolong the life of the microchannel image intensifier tube. Its lifetime is also dramatically reduced if its input level exceeds 5×10^{-4} fL illumination level. In normal room light, a 2.3 density filter should be used in front of the imaging lens; in sunlight, two such filters in series should be used.

The accessary power supply has a power ON-OFF switch as well as switches for turning each of the laser diodes on or off.

2.2 INTERNAL COMPONENTS

A schematic of the correlator's optical system is shown in Fig. 2-3. Two laser diodes (LDs) are located symmetrically on opposite sides of the image intensifier and LCLV assemblies. The light from the diodes pass through a half-wave plate to rotate their polarization 90° for optimum diffraction by holographic lenses. A mirror directs light from each diode toward a holographic lens.

Each of the two holographic lenses diffracts light from one of the LDs toward the LCLV in an array of fifteen converging beams. The polarizing beam splitter allows most of the incident light to reach the LCLV. On reflection, the light with rotated polarization is reflected from it and continues to the filter array. At the filter array the light focuses into a three by five array of spots, or Fourier transforms, from each of the two LDs, for a total of thirty Fourier transforms. Light diffracted by the filter array emerges as parallel rays and are focused on the TV camera sensor by a simple lens.

Several components have some adjustment for system alignment. The LDs can be adjusted along the optical axis by adding or removing shims from its base; the two mirrors after the LDs have a one axis rotational adjustment; the filter holder frame can be adjusted along the optical axis for focusing; and the camera can be adjusted along optics axis for focus.

2.3 OPERATION

> <u>CAUTION</u>: The life of the image intensifier will be drastically reduced if exposure significantly exceeds 5×10^4 fL. Use of external light attenuator is required in normal room light and in sunlight.

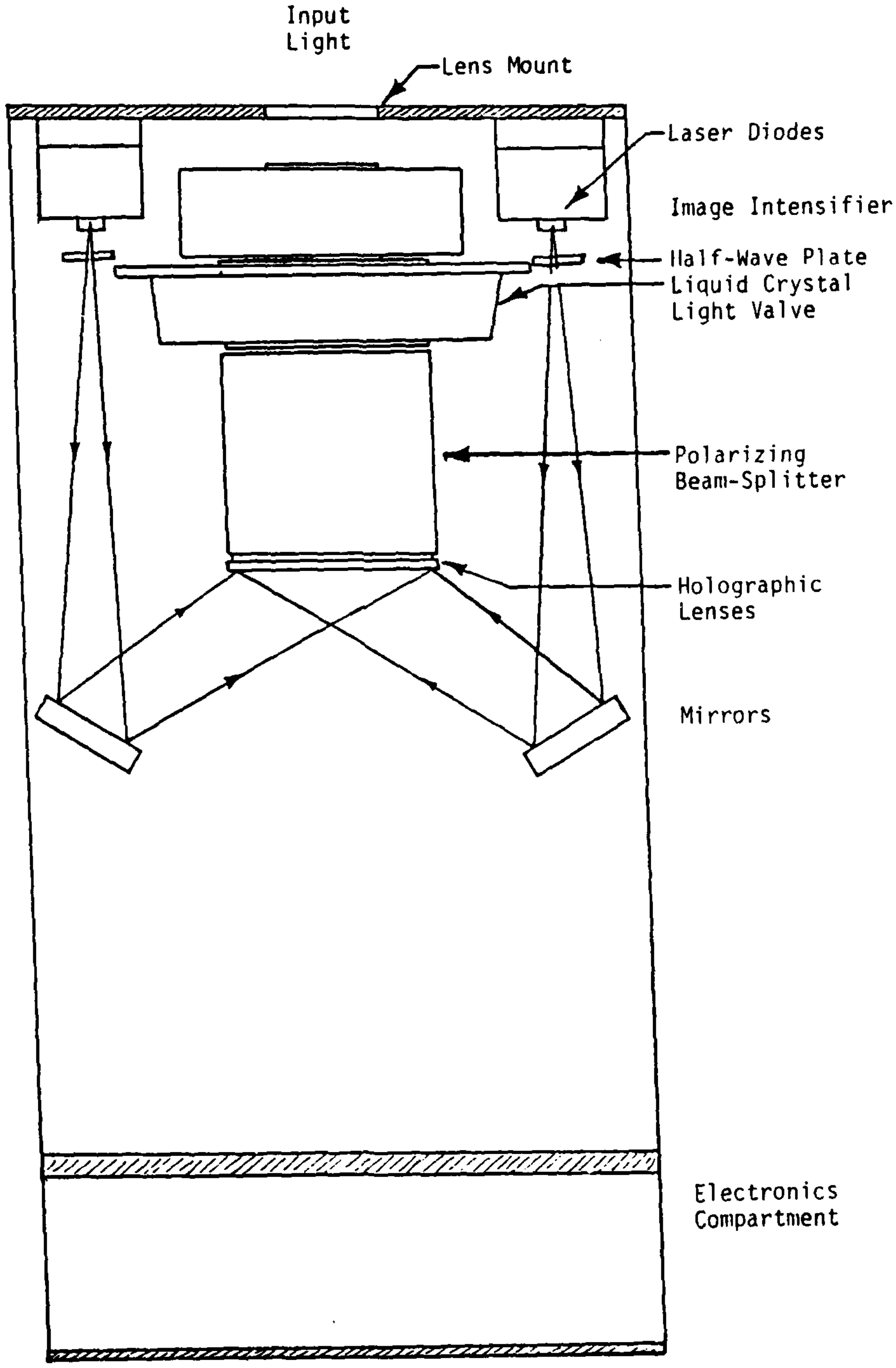


Figure 2-3. Optical system layout of the correlator:
(a) cross-sectional view through laser diodes and

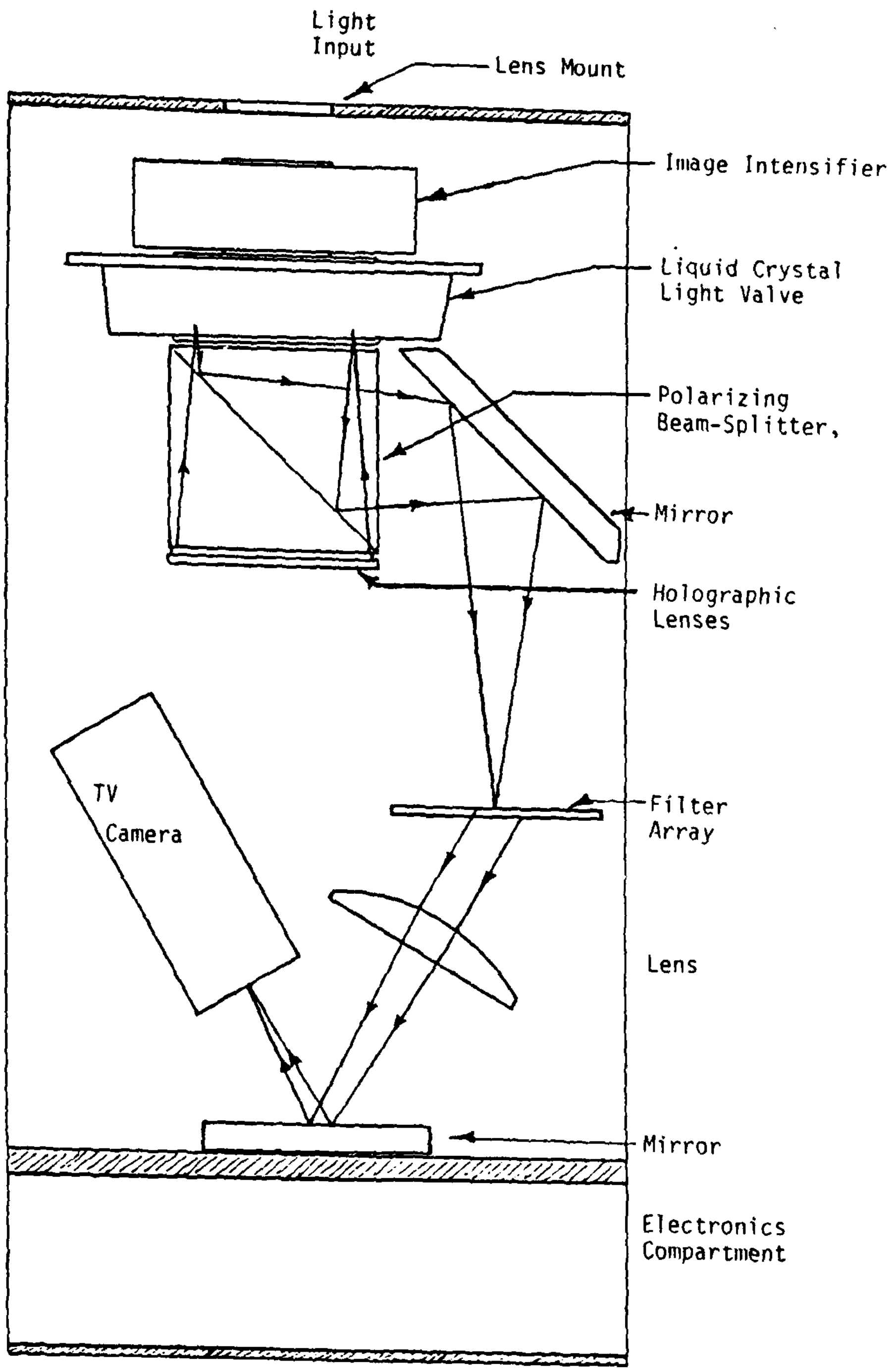


Figure 2-3. (b) cross-sectional view through filter array.

Before turning the power on for the correlator, cover the imaging lens with a lens cap. Switch the ON-OFF switches of both LDs to OFF position, then turn power ON and allow the LD temperature control circuits to reach their normal operating levels. After about 10 minutes normal operating temperature has been reached and temperature has stabilized.

The filter plate should be inserted with the glass side toward the back of the correlator. Once inserted, press the filter frame sideways to rotate the frame about the pin that fits the notch in the frame to assure proper seating.

Be sure that the light level will not exceed the image intensifier rating. Image intensifier irradiance is given approximately by

$$I = \frac{I_i[10\exp(-D)]}{\pi(F)^2}$$

where I_i is scene luminance in foot-lamberts, F is the lens f-number setting, and I is the image intensifier illuminance in fL. Two external attenuators are provided, each having density D=2.3. Either one, or both in series, may be used.

A zoom lens provided with the correlator allows scale change of the input object. Correlation can be expected when the scale and orientation of the input scene matches the one recorded on the filter. If each filter is different, then background noise can be reduced by turning off one of the LDs that illuminate filters which do not match.

The correlator was designed not to require readjustments after initial alignment. Testing revealed, however, that alignment is time dependent, presumably caused by thermal changes in the correlator structure. For this reason operating in constant temperature

environment is highly desirable. Some adjustments can be made by tilting the mirrors and by pushing the LDs slightly sideways.

For the scene to match filter orientation in the correlator, the correlator should be positioned with the filter in a horizontal position, on the right-hand side, as viewed while looking at the input scene.

3.0
FILTER MAKER DESCRIPTION AND OPERATION

3.1 DESCRIPTION

The filter maker consists of two major components: the electronic control console and the optical system for filter recording. Fig. 3-1 shows the control console and Fig. 3-2 shows part of the filter maker system mounted on a bread board. Fig. 3-3 shows the optical system layout. Filter maker alignment, filter plate positioning reference beam angular alignment, and exposure are all controlled by a program stored and executed by a personal computer (PC).

The filter maker operates in the following manner. An image of the scene of which the filter is to be made is displayed on a high-brightness TV screen on the bread board, and also on a TV monitor on the control console. On the bread board, the TV display is imaged onto a liquid crystal light valve (LCLV) coherent light modulator. This modulator is illuminated by a laser diode whose output is collimated, its aspect ratio corrected, and expanded to 50mm diameter. An off-the-shelf laser diode assembly was used that included temperature and output level control. A beam splitter in front of the diode assembly reflects part of its output toward a detector. A shutter is also inserted at this location for exposure control.

After beam expansion to 50mm diameter, the beam is divided into two parts by a polarizing beam splitter: one part is reflected toward the LCLV, the other part passes through the beam splitter and is reflected by two mirrors toward the filter recording plane. The second mirror can be rotated about two axis to adjust the reference beam angle. This adjustment is needed to achieve parallel ray diffraction from all filter positions in the correlator. The mirror is adjusted by two stepping motors under computer control.

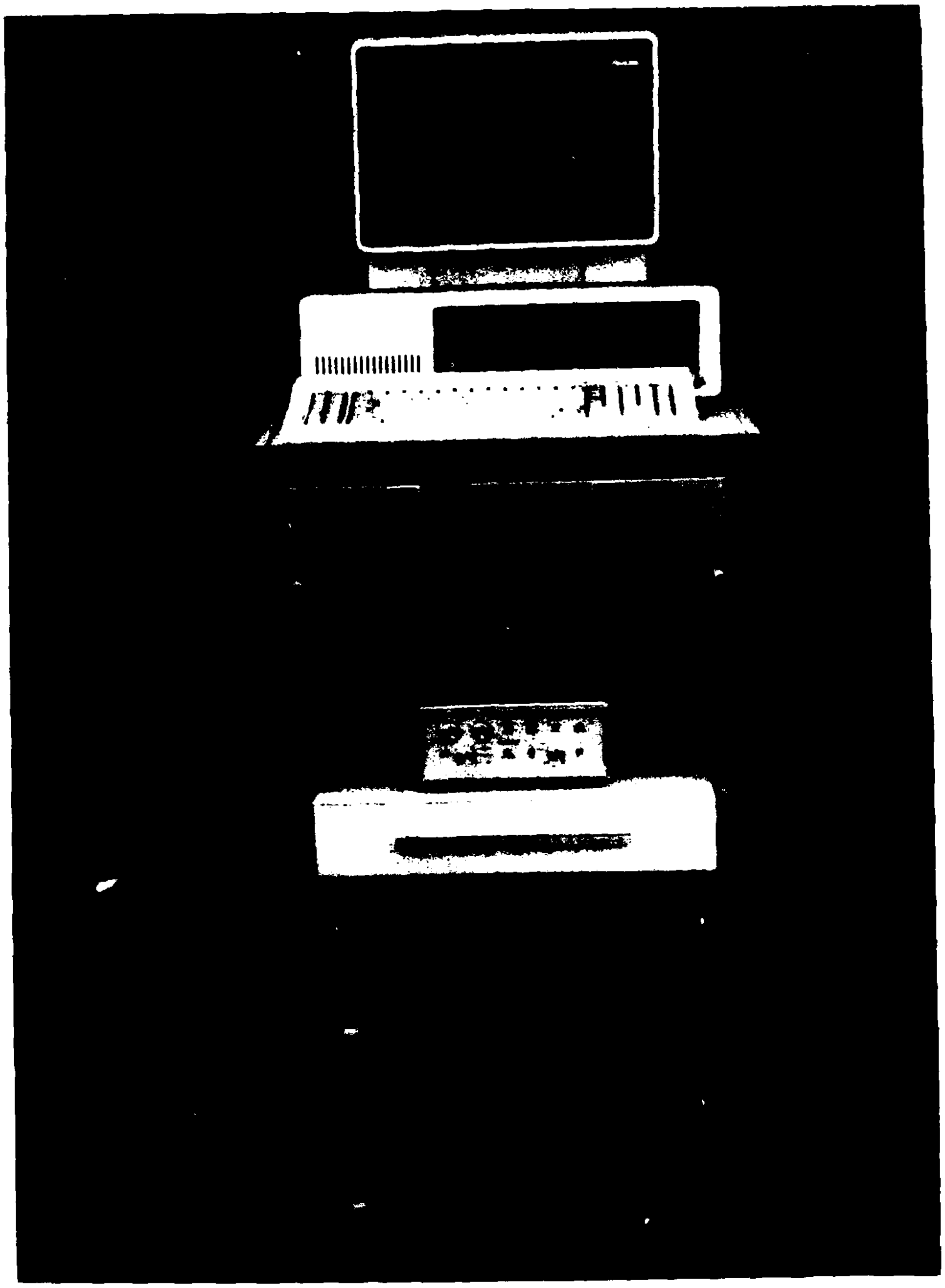


Figure 3-1. Filter maker control console.

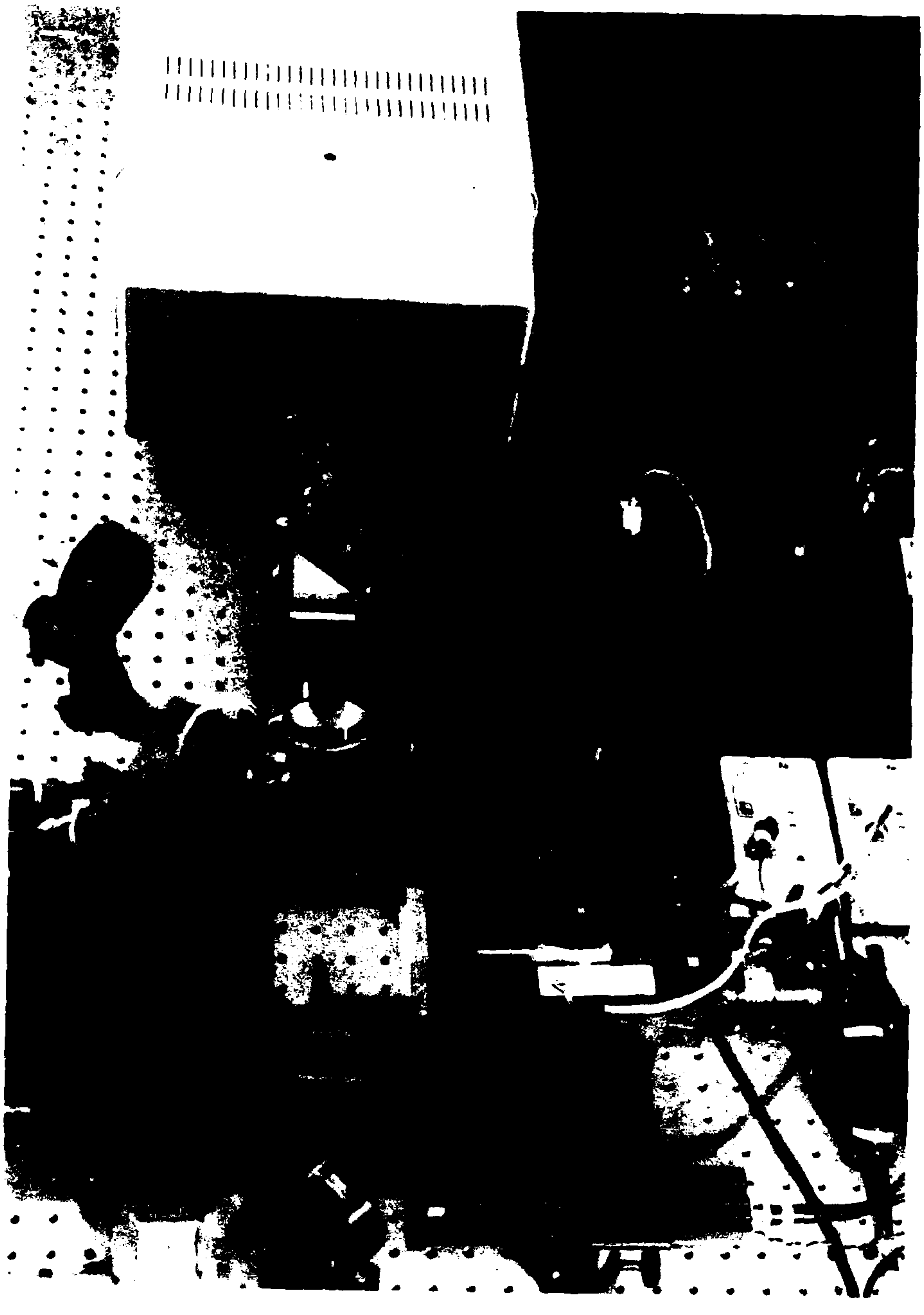


Figure 3-2. Photograph of filter maker optical and mechanical components.

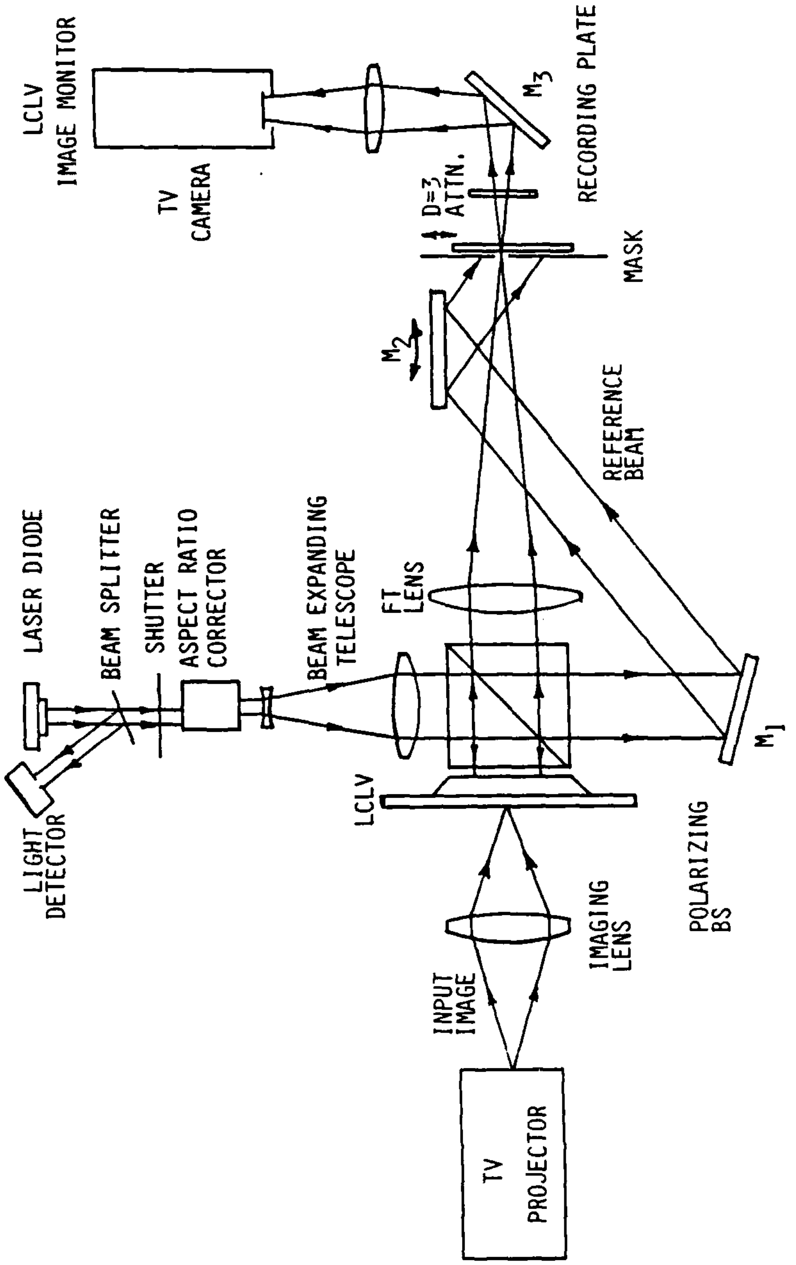


Figure 3-3. Optical system layout of the filter maker.

The other beam is modulated by the LCLV and contains the signal of which a filter is to be made. After passing through the polarizing beam splitter, it passes through a lens and its Fourier transform is displayed at the filter plane. A mask in front of the plate allows a small part of the plate to be exposed at one time.

The filter is mounted on two orthogonal translating stages driven by stepping motors under computer control. Resolution of these stages is one micrometer. The unexposed photographic plate is mounted in a stainless steel frame, shown in Fig. 3-4, for repositioning accuracy of $\pm$ 0.2 μm.

Behind the filter plane a mirror and a miniature TV camera is located. The LCLV is focused on the TV camera to monitor the LCLV output. This image is displayed on a second TV monitor next to the one displaying the input image. This arrangement allows continuous observations of both the input video signal and the output of the LCLV.

An automatic indexing feature of the filter was included to compensate for filter misalignment due to filter maker temperature changes. A quadrature photodetector cell is mounted in a photographic plate frame, shown in Fig. 3-5, and is inserted in the filter holder during the indexing procedure. The appropriate pairs of detectors are connected to a differential amplifier to detect misalignment with respect to the focused signal beam. This difference signal is fed to the computer which drives the translating stages in the proper direction until balance is achieved. The accuracy of this arrangement depends upon the focused spot brightness and ambient light level. Typical accuracies are $\pm 2\mu$m.

The control console shown in Fig. 3-1 contains most of the electronic equipment for the filter maker. At the bottom are two stepping motor drivers/controllers, above it is the electronic shutter

Figure 3-4. Stainless steel frame for photographic plates.

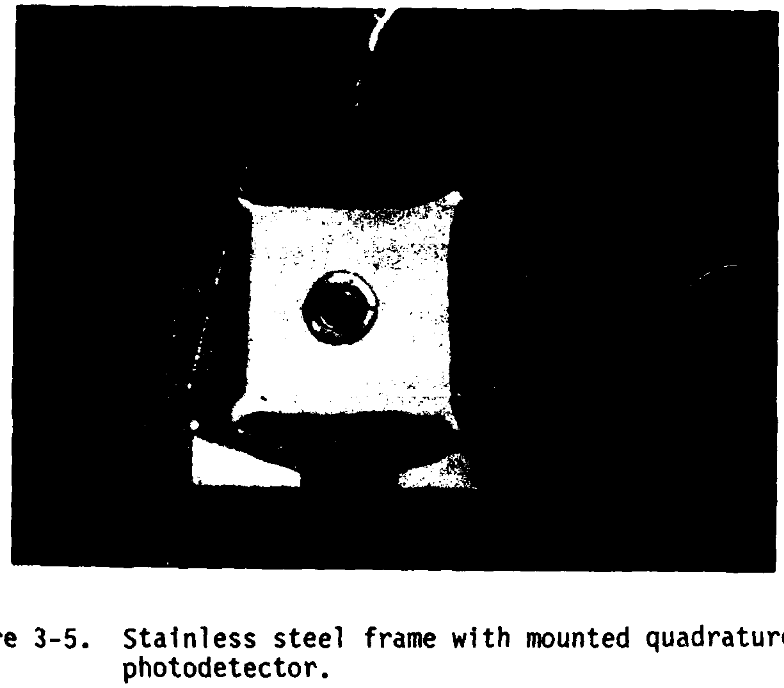


Figure 3-5. Stainless steel frame with mounted quadrature photodetector.

control unit, two TV monitors, and an IBM personal computer system is at the top. Filter recording can be either fully automatic or semiautomatic, and is controlled by a program written in IBM BASICA language. All routine operations or parameter changes can be selected from a menu.

Time required to record thirty filters depends upon exposure time settings and time required to change the input video signal. Typical time for 30 filter recording is 5 to 10 minutes.

3.2 FILTER MAKER OPERATION

Power to the filter maker is routed through two outlet strips with switches. While all components could be switched on at the same time, the surge would be considerable and is not recommended. High-power units should be turned on individually: PC, the two stepping motor drivers/controllers, and the high-brightness TV monitor on the bread board. The laser diode controller should be turned on with the laser power output control set to zero and temperature setting at 19.3^{o}C. After about 10 or more minutes the laser diode output should be adjusted to 19.6mW output and the function switch on controller should not be left at output adjust setting, as the LD is inherently unstable at this setting. Both the temperature and power settings are important as they determine the wavelength of LD output. The above choices represent a stable operating point determined experimentally. Other stable power-temperature settings exist.

Filter positions on the photographic plate are shown in Fig. 3-6, as viewed when looking into laser light. The recorder program has three exposure sequence choices, as listed in the main menu shown in Fig. 3-7.

Choice #2, AUTOMATIC EXPOSURE SEQUENCING, exposes all filters between and including first and last filter specified. Input image can

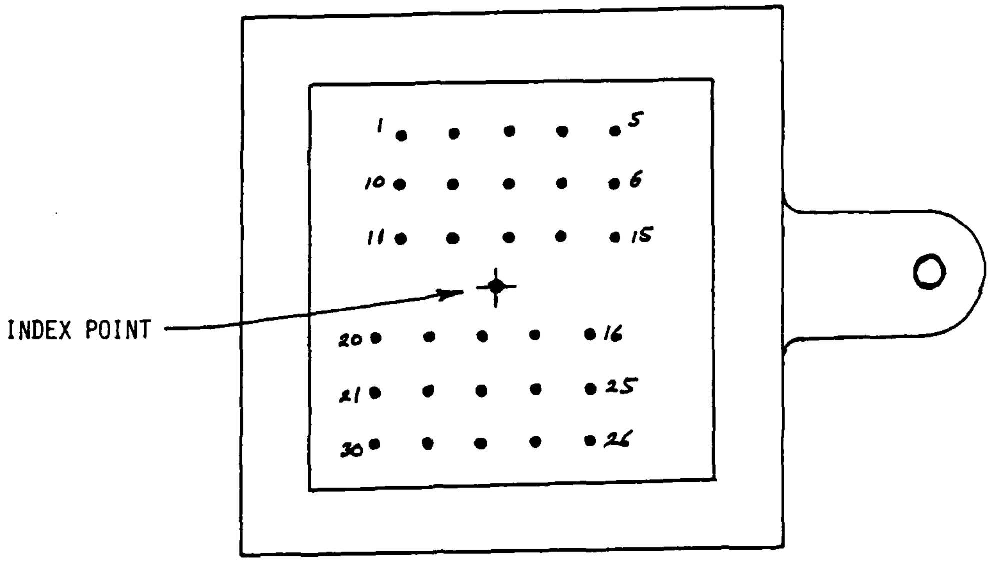


Figure 3-6. Filter positions on photographic plate looking into laser light.

```
FILTER PROGRAM MAIN MENU

    1. STAGE REFERENCE

    2. AUTOMATIC EXPOSURE SEQUENCING

    3. MANUAL EXPOSURE SEQUENCING

    4. SINGLE EXPOSURE

    5. SET PARAMETERS

    6. END PROGRAM

ENTER SELECTION NUMBER
```

Figure 3-7. Filter program main menu.

be changed during the SETTLE TIME, which is the time allocated for the system to stabilize after filter plate translation. A TTL level pulse is also available to trigger an external device capable of changing the input video signal.

Choice #3, MANUAL EXPOSURE SEQUENCING, is the same as choice #2 except that the sequence stops after each exposure to allow a change of input image. Pressing any key once on the PC restarts the sequence.

Choice #4, SINGLE EXPOSURE, is designed to allow single exposures at any of the 30 filter positions.

The automatic filter recording program has two system checks built into it. One, it checks the laser to see if it is on. If power level is too low, a message appears on the screen. The second check is on shutter operation. If the shutter is in an incorrect position or if it does not operate, an error message will appear. The exposure sequence can be interrupted by holding down any key of the PC.

The operating procedure for the filter maker is summarized below:

1. Turn power ON for all equipment. Insert disc into drive A of PC.

2. Wait about 10 min. for temperature of laser diode to stabilize at 19.3^{o}C, then adjust output to 19.6 mW, and turn function switch to actual temperature readout.

3. Load BASICA program in computer, then load program FILTER, then RUN program.

4. Follow instructions as they appear on screen. The first instruction is to reset Unidex controllers. The appearance of PC monitor screen after a key is pressed to continue is shown in Fig. 3-8.

```
FILTER PROGRAM

SET-UP

RESET UNIDEX CONTROLERS

PRESS ANY KEY TO CONTINUE

HOMING POSITION AND ANGLES
```

Figure 3-8. PC monitor screen display after any key is pressed once.

```
PARAMETERS

    1. EXPOSURE TIME (SEC)                  5
    2. SETTLE TIME (SEC)                    2
    3. FEEDRATE                             4000
    4. TIMEOUT COUNT                        5000
    5. LASER POWER THRESHOLD                100
    6. RETURN TO MAIN MENU

ENTER PARAMETER NUMBER
```

Figure 3-9. PC monitor screen display after selecting choice #5 from main menu.

5. After initial homing sequence is completed, the menu will appear, shown in Fig. 3-7. The next step is to establish stage reference. For reference to be accurate, LCLV exitation must be on, CRT must have a bright field, and reference beam should be blocked. <u>Quadrature detector must be in place</u> in the filter holder. Shutter must be in closed position at the beginning of this procedure. This sequence accurately establishes relative position of translating stages to the point focus. Choose #1, STAGE REFERENCE.

6. After stage reference sequence is completed, the main menu will appear again. If exposure time, settle time or laser power threshold require a change, select #5, SET PARAMETERS. The screen shown in Fig. 3-9 will appear. Change parameters as needed, then return to main menu by selecting #6.

7. With lights out, place an unexposed photographic plate mounted in a filter holder into recording position. Place appropriate video display on the TV monitor and proceed with the exposure sequence.

8. If considerable time elapses between STAGE REFERENCE sequence and filter recording, the STAGE REFERENCE sequence should be repeated to compensate for misalignment due to thermal expansion.

3.3 PROCEDURE FOR ALIGNING FILTER POSITIONS IN FILTER MAKER

The alignment is accomplished by recording point focii of laser diodes in the correlator on a glass plate and then determining the corresponding stage coordinates in the filter maker. In addition, the index point of the filter maker can be recorded on the same plate. The processed plate is then placed in the filter maker and the point focus of the beam is observed on the TV camera with a D = 3 attenuating filter in front of it. A 23 to 16mm focal length microscope objective should be used to project the point.

The Filter Maker is first aligned by proceeding through the STAGE REFERENCE step which drives the stages to align them with the index point. Then the plate with recorded filter positions is inserted and the microscope objective is aligned to project the point focus on the camera. The index point should be in good alignment. If it is not, the system should be rechecked to see if something affected the indexing accuracy, such as: LCLV exitation off, CRT brightness down, laser diode beam low, shutter closed, or reference beam not blocked.

Once the index point alignment is accurate, one can proceed to determine coordinates of each filter. This is done by resetting the stage drives and their counters to zero using Unidex controller directly rather than the PC, checking alignment visually, and recording digital readouts of stage positions. These numbers are the ones to be entered as data points in the data statements of the program FILTER (lines 20,000 to end of program).

The points in each 3 x 5 array are spaced approximately 5200 steps apart. If some data are available from previous measurements, the stages can be driven to those positions using "IMMEDIATE" mode of stage controllers, and then fine adjustments can be made by either using "SLEW" mode for rapid motion motion or "STEP" mode for single step (1 micron/step) mode. The procedure for aligning 30 filter positions may take two hours. If room temperature changes during this time, the index point may have shifted. To check, return to index point by driving the stages to zero digital readouts, and observe alignment accuracy. If misaligned, then filter position coordinates may also represent misaligned positions.

4.0
SYSTEM DESIGN

4.1 CORRELATOR

The requirement of addressing 30 filter positions and of packaging the correlator into a cylinder 150mm diameter by about 250mm in length made the design rather difficult. To package the correlator into such a small volume required a careful choice of components and folding of optical paths. The choices made and the reasons for them are briefly described here.

To convert the incoherent input image to a coherent one required the use of the Hughes Aircraft liquid crystal light valve (LCLV) since that was the only one available. Specifications of the LCLV and the correlator input light level necessitated the use of an image intensifier. We choose an ITT microchannel intensifier tube in part because it was very compact. Reports were found in the literature [1] of obtaining satisfactory results using this unit. While the LCLV has a resolution of about 30 l/mm, the image intensifier by itself has about 15 l/mm resolution and the two units together have a reported effective resolution of only 8 l/mm. Thus, the resolution of the input system is greatly reduced in order to achieve low light-level operation.

Several options were considered for the coherent system. While a laser diode (LD) was an obvious choice for the light source, several layouts were considered for the optical system. Fig. 4-1 shows a layout employing a separate collimating and Fourier transform (FT) lens. Major difficulties with this layout is that the FT lens has to operate at diffraction-limited performance over a 10^0 field of view, that such a lens would require custom design and manufacture for operation at 780nm, that the physical space occupied by this lens would be considerable, and that in addition a Fourier transform multiplexer device would have to be designed and fabricated. FT multiplexers have been reported in

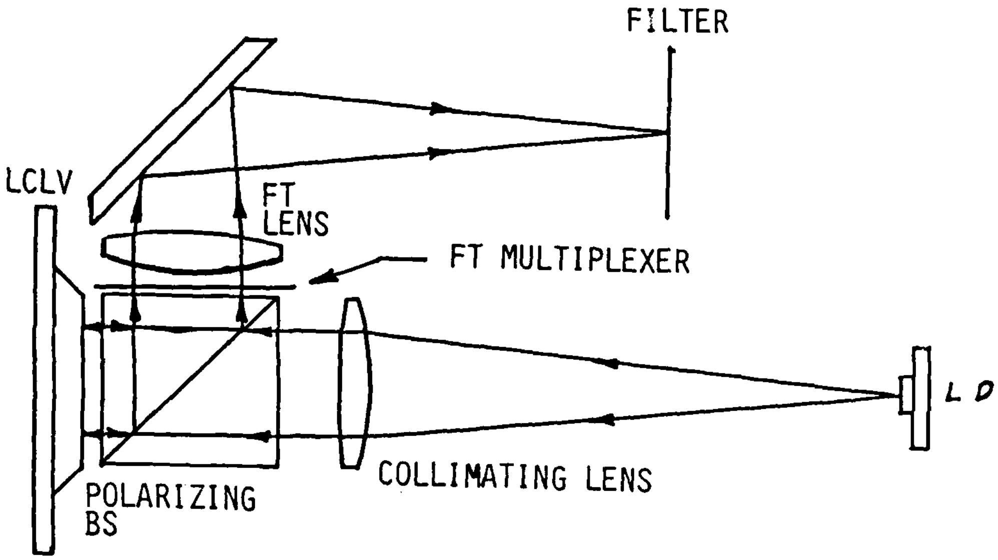


Figure 4-1. Compact correlator layout employing two conventional lenses.

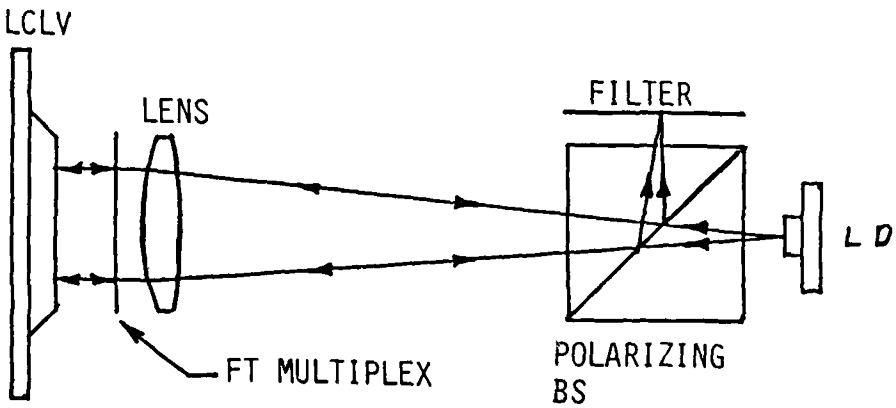


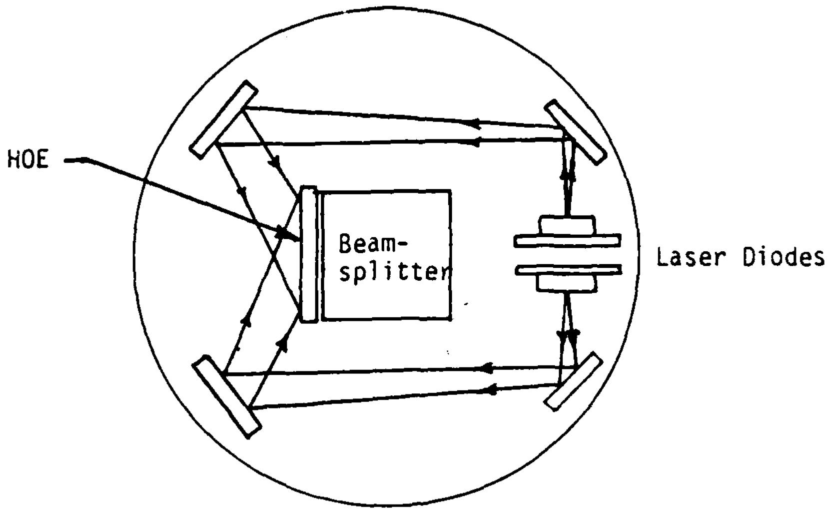
Figure 4-2. Compact correlator layout employing a single conventional lens.

literature [2] for up to 25 FT's, but uniform light distribution was not achieved. Such a structure does not yield readily to 30 FT generation since usually the array is rectangular with odd number of filters along each axis, such as 5 x 5 for a total of 25 FTs or 7 x 7 for a total of 49 FTs. For this reason this approach was abandoned.

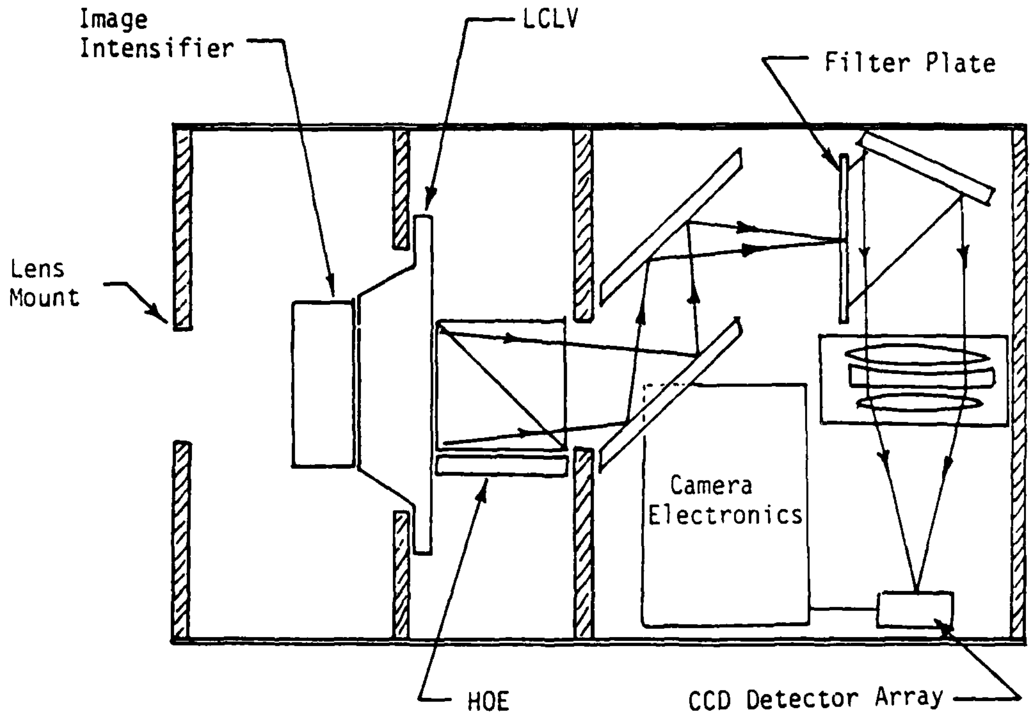
Another layout is shown in Fig. 4-2. Here a single lens is used for both collimation and FT, and the system would be somewhat more compact that the previous one. The lens requirements are somewhat more demanding than before because diffraction limited performance must be achieved through some 50mm thickness of glass. Also, the design and fabrication of the FT multiplexer is made more difficult by the light beams passing through the multiplexer twice.

To overcome the above difficulties we decided to use two holographic optical elements (HOEs) to generate the required 30 FTs. Such HOEs offer several advantages in a system like this. One, a HOE can be recorded through any glass thickness at any angle and still achieve diffraction-limited performance. Two, FT multiplexing can be achieved by simply recording a hologram of multiple point sources. Three, the aspect ratio (width-to-length) of the beam can be corrected somewhat by selecting proper geometry; four, by using two HOEs and two LDs, 15 instead of 30 filters can be addressed at any one time reducing noise buildup in the inverse FT plane; and five, the HOEs are very thin and do not occupy much space.

Fig. 4-3 shows the initial configuration for the layout. We had difficulty in fitting all of the components within a 150mm diameter cylinder and eventually choose for the layout shown in Fig. 2-3. All of the required optical components could be located within the 150mm cylinder 250mm long except for the imaging lens. Mounting of electronic components required additional 50mm length, for a total of 300mm.



(a)



(b)

Figure 4-3. Initial compact correlator layout employing two HOEs: (a) laser diode section and (b) longitudinal section.

A 30mW laser diode operating at 780nm was selected for a light source. A shorter wavelength requires lower exposure and for this reason a laser diode with shortest available wavelength was selected. The wavelength of the LD is dependent upon temperature and its temperature must be controlled. Fig. 4-4 shows an exploded view of the laser diode assembly including thermoelectic cooler and heat sink.

The inverse FT was accomplished by a separate glass lens rather than a built-in lens in each FT filter. Due to the distribution of FTs over a 40 x 40mm area and the large, 30^{o}, offset angle, the effective focal lengths of FTs would vary considerably making it impossible to achieve the same deflection from each FT for the same input image translation. For this reason all filters are recorded with collimated reference beams and an inverse FT lens focusses the diffracted light. The focal length was chosen as short as available for a 50 mm diameter simple lens, which was 100mm. The correlation spot is detected by a miniature solid state TV camera mounted within the correlator assembly.

4.2 PLATE HOLDER

An essential requirement of the correlator is that the photographic plate can be replaced with a high degree of accuracy so that realignment would not be needed. The lateral required alignment accuracy was $\pm$ 12 seconds of arc. Due to the fragility of glass, metal frames for holding the glass plates were designed that would fit into a specially designed filter holder. Fig. 3-4 shows a photograph of a metal frame and Fig. 4-5 shows the filter holder. Magnetic stainless steel was selected as the material for the frame to resist effects of photographic chemicals and to enable magnets to hold it in place. Glass can be cemented into this holder prior to exposure.

The filter holder contains three steel pins with spherical tips that define the filter plane, and two cylindrical steel pins that define both

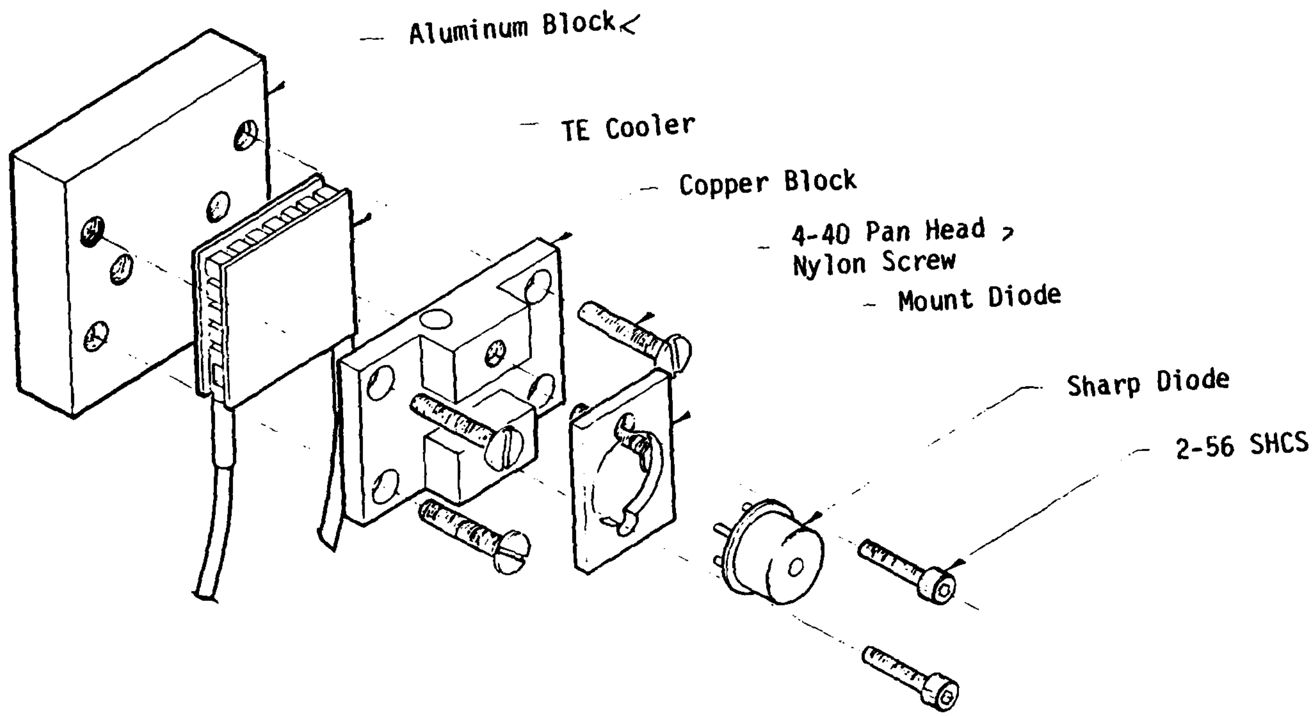


Figure 4-4. Exploded view of laser diode assembly designed by Liconix.

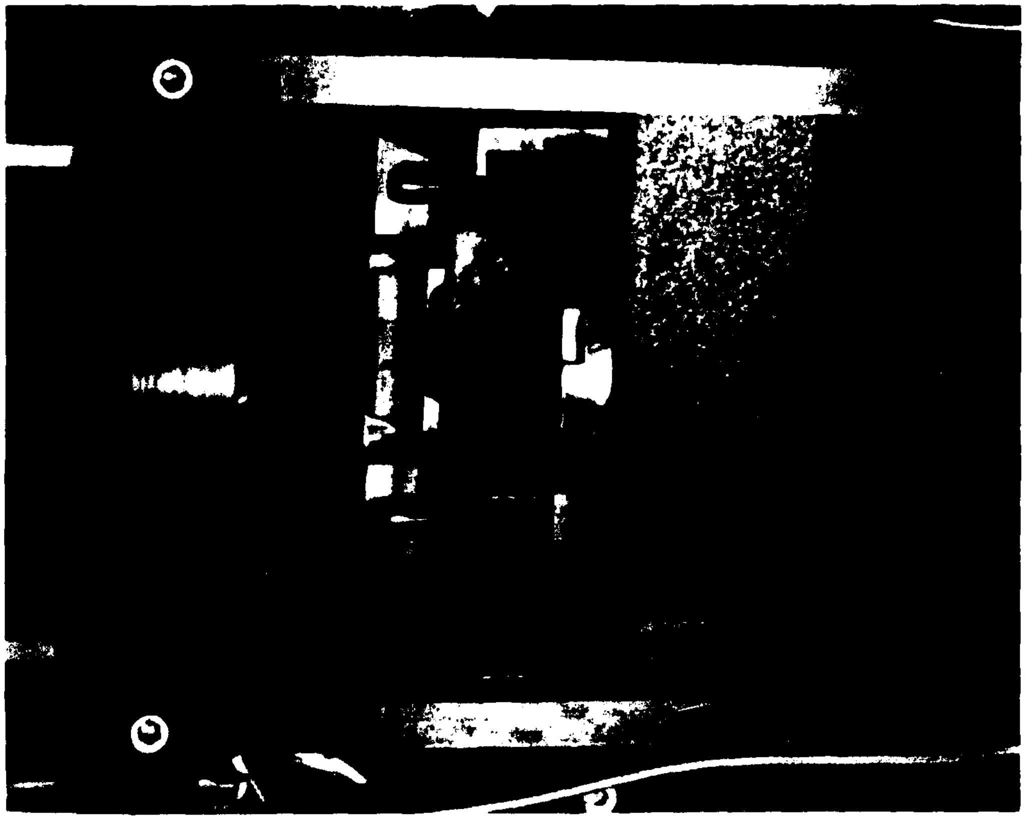


Figure 4-5. Filter holder assembly mounted inside the correlator. Two locating pins and three square magnets are visible in the back.

the lateral position and angular alignment. The notch-type recess provides two-dimensional position repeatabilty while the flat portion of the slide insures angular position repeatability.

Miniature magnets were mounted in the holder to pull the frame against the locating pins. This mounting arrangement provides excellent repeatability in frame replacement.

4.3 FILTER MAKER

The optical system for the filter maker was shown in Fig. 3-3. A major design choice was the selection of a method to implement the multiple filter recording feature. One possibility was to have a fixed recording plate and reference beam, and to rotate the converging signal beam. This approach has several requirements that are difficult to implement.

First, a mirror that reflects the signal beam must be separated from the Fourier transform (FT) plane by the same distance as is the HOE from the FT plane in the correlator. If these distances do not match, correlation peaks will not register at the output plane of the correlator.

Second, to achieve filter position accuracy of $\pm 2\mu m$ with 200mm converging beam, the angular accuracy must be $\pm 10^{-5}$ radians or ± 2 arc seconds. Common repeatability for rotating tables is ± 0.2 arc minutes. An extremely precise table would be needed with this method.

Third, rotation of the converging beam would cause the point focus to move in an arc rather than in a plane. Focus adjustment would be needed for each filter position.

For these reasons we selected a method that requires much lower accuracy from the rotating stages and high accuracy from translating stages, which are readily available. In this method the converging beam remains stationary, the recording plate is translated relative to it, and a collimated reference beam is angularly adjusted for each filter position. By this choice the system was made simpler and could be assembled with readily available components.

To input images in real time from a video source, a CRT display device and LCLV valve were needed. A hight-brightness projection TV system was selected to meet the LCLV illuminance requirements. Additional magnets were mounted on the CRT to eliminate image distortion. A Nikon camera lens imaged the CRT on the liquid crystal.

For the light source, a prepackaged laser diode with temperature and current control was selected. The collimated output passes through a beam aspect ratio corrector and then a beam expanding telescope to achieve 50mm diameter. The laser diode has the same wavelength, 780nm, as in the correlator.

An important requirement was to have the filters recorded with $\pm 2\mu m$ accuracy. Thermal expansion of the rather large filter maker base can cause considerable error and means for compensating for this was needed. We decided to use an optical index system employing a quadrature detector mounted on a filter support frame to automatically establish a precise index point. This point is precisely aligned with the point focus of the converging signal beam. Linear translating stages are driven to the approximate location of the detector and then the outputs of the opposite detector cells are compared. If not equal, the stages are driven until the output is balanced in both directions. An accuracy of $\pm 2\mu m$ can be achieved by this method.

To monitor the input image, a TV camera and a lens were located after the filter plane to image the LCLV. It is possible to observe the input video image on one monitor and the output of the LCLV on an adjacent monitor.

5.0
HOE FABRICATION

The correlator design called for the fabrication of two HOEs, each of which would focus light to 15 points in a 3x5 array. One way to generate fifteen points to be recorded in a HOE would be to mount fifteen small lenses in a 3x5 array and to illuminate them with a collimated beam. Mechanical mounting of the lenses would not be very precise and in addition the actual focal lengths of the lenses are not exactly the same due to fabrication tolerances. Therefore, all the point focii would not be exactly in the same plane. A more precise method of generating the point array was needed.

5.1 HOE ARRAY FABRICATION

We decided to generate the fifteen point sources by recording a hologram array on a microflat plate, each hologram being the recorded interference pattern between a point source and a collimated beam, as shown in Fig. 5-1. The plate was translated by two orthogonal precision stages driven by stepping motors having one micrometer resolution. The precision stages assured exact spacing between HOEs and exact focus in the same plane. The translation, dwell time to allow vibrations to damp out, and exposure times were all controlled with a personal computer. The whole recording process was automatic, insuring accuracy and precision.

Several difficulties were encountered in fabricating the HOE array. Since the laser diode output is collimated and passes through a circular aperture, the beam intensity pattern is not Gaussian. This causes concentric fringes in the beam after the pinhole. These circular fringes were very pronounced but where suppressed in the recording process by adjusting exposure to a region where diffraction efficiency is constant relative to exposure. No fringe pattern was evident in the reconstructed beam.

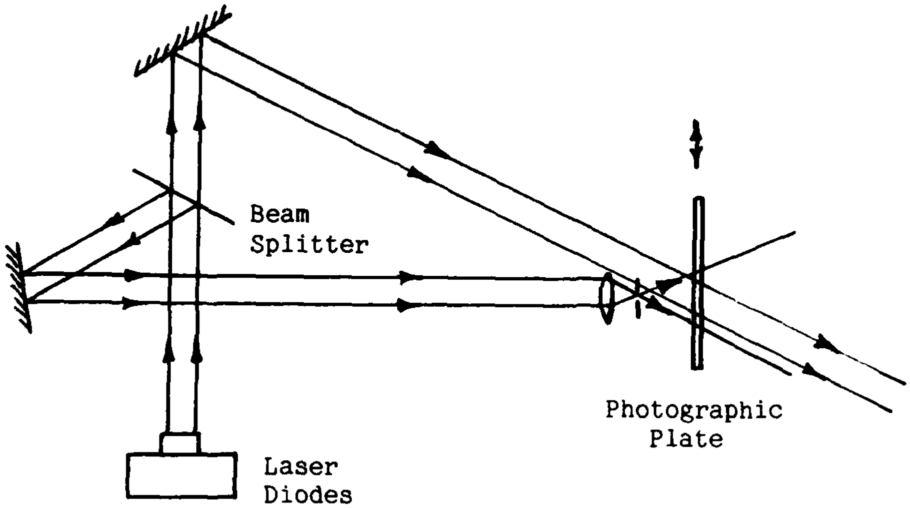


Figure 5-1. Optical system for recording HOE array.

Figure 5-2. Photograph of HOE array.

Another problem was discovered after observing random variations in diffraction efficiency of different HOEs in the array. This was traced to mode (wavelength) changes in the laser diode during exposure time. We discovered that this was a common occurrence when the laser diode power supply controller is left in output adjust mode. This setting is the only one in which the diode power output is displayed. Once the cause of this problem was discovered, the controller was set to another position and wavelength shifts during exposures ceased.

Mode hopping may also occur if the diode is operated near a temperature and output power setting where discontinuity in wavelength vs. temperature occurs. Measurements were made to locate a midpoint between two discontinuities and the laser diode was set at this point. One such point is 19.3^{o}C and 19.6mW output power. All HOE's were made at these settings and with the controller switched to LD temperature display mode to avoid mode hopping.

The sensitivity of photographic film is either low or zero at the laser diode output wavelength of 780nm. After testing all available Kodak and Agfa holographic emulsions, two were found to have a reasonable sensitivity: Kodak 120 emulsion and Agfa 8E75. Both require approximately 20mJ/cm^2 exposure for an efficient bleached HOE, which is 250 times more than the required exposure at 633nm.

The HOE array was recorded on 0.25 inch thick Kodak 120 microflat glass plate. Typical exposure times were 0.2 seconds. The plates were then developed and bleached according to the procedure shown in Table 5-1. This particular procedure was chosen because of its simplicity, low grain scattering, and efficiency. We discovered, however, that plates processed in this manner loose efficiency and become dark after several week exposure to room lights. After this effect was discovered, plates were kept covered except when in use. The efficiency of the processed plates was as high as 45% at 633nm wavelength. Fig. 5-2 shows the HOE array with each HOE approximately 5mm in diameter.

Table 5-1
HOE Processing

1. Develop for 6 min. in Kodak D-19 developer at $20^{o}C$.

2. Rinse in water for 30 sec.

3. Fix in Hunt's fixer without hardner for 5 min.

4. Wash for 10 min. in running water.

5. Bleach until plate clears in Kodak R-10 bleach, part A only, diluted to one part A to 30 parts water.

6. Wash for 10 min. in running water.

7. Dry.

5.2 LARGE HOE FABRICATION

Fabrication of the correlator HOE element requires a large converging reference beam. Some distortion is needed in this beam so that when the final HOE is illuminated through a glass cover plate at a 60^{o} angle, aberrations would not be introduced. Such a beam can be generated by placing a tilted glass plate in the diverging beam and recording it on a HOE. The optical system shown in Fig. 5-3 was used to record the large HOE. An exposure time of 70 seconds was required to achieve maximum diffraction efficiency. The plate processing was the same way as for the HOE array, as listed in Table 5-1. Efficiencies in the 25 to 35% range were achieved.

5.3 FINAL HOE FABRICATION

Fabrication of the final HOE required recording of the interference pattern between fifteen point sources and a converging reference beam. In order to avoid aberrations, the fifteen point sources had to pass through the same thickness and type of glass as in the correlator. This total thickness of glass was 10cm. Also, the reference beam had to be such that after passing through HOE cover glass at 60^{o} angle, a perfect Airy disc pattern would be formed.

The initial system for the final HOE fabrication is shown in Fig. 5-4. The laser diode beam was expanded to 70mm diameter and collimated. The beam was split into two parts, one illuminating the HOE array and the other the large HOE. Two polarizing beam splitters were placed between the HOE array and the final HOE location to duplicate the light path in the correlator twice through the beam splitter. Distance from the HOE array to the final HOE, and from the final HOE to the point focus of the converging reference beam, were carefully adjusted to match the distances in the correlator. Light shields were added around the beam splitter cubes to reduce light scattering from corners of the cubes

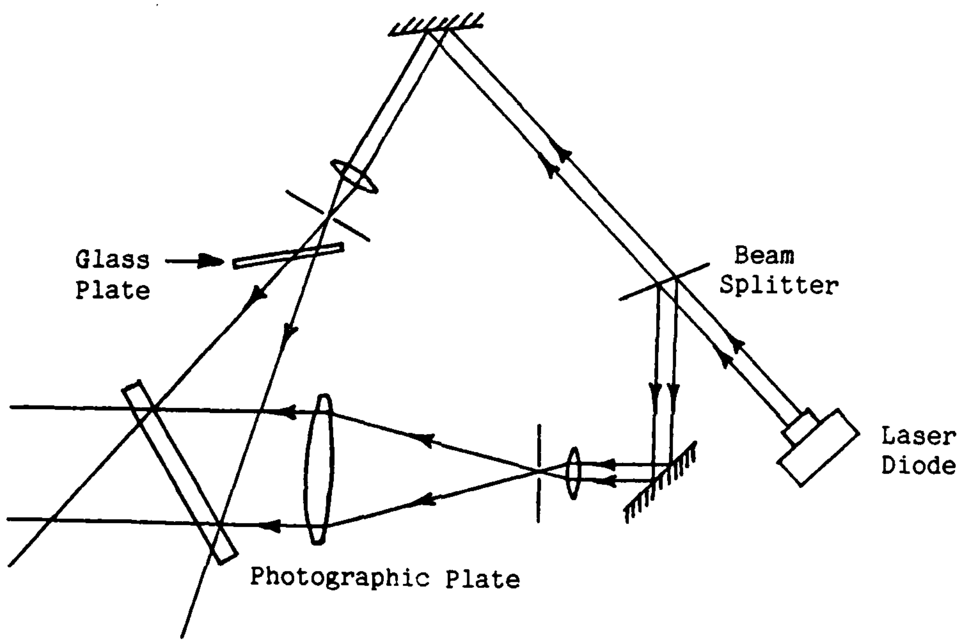


Figure 5-3. Optical system for recording the large HOE.

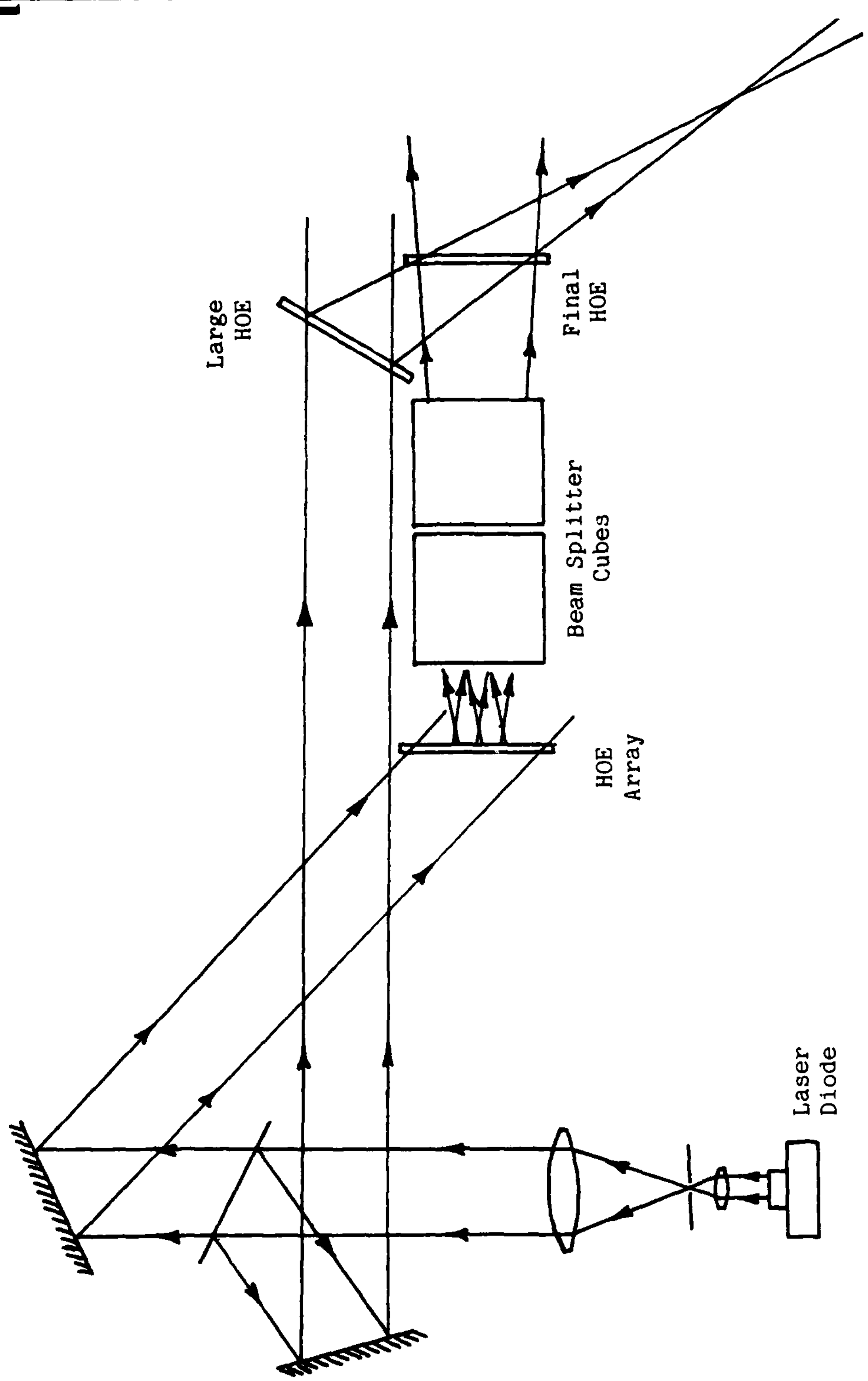


Figure 5-4. Initial optical system for recording the final HOE.

and reflections from their sides. A microscope with a solid state TV camera was set up to observe the point focus quality of the converging beam from the large HOE. With a recording plate in place, the point should appear to be a perfect Airy disc.

Exposure tests indicated that with a 12 minute exposure a density of 0.7 could be reached. This density was much too low for efficient recording. In order to achieve greater densities, the recording plates were hypersensitized in 1.12% solution of amonium hydroxide. The plates were hypersensitized by soaking them in amonium hydroxide solution for 45 seconds and then drying them. Hypersensitized plates have to be used the same day, otherwise the fog level will be high. The required exposure for hypersensitized plates was about 26,000 ergs/cm^2.

The recorded final HOE's were checked in visible helium-neon laser light for diffraction efficiency and scattered light level. The scattered light level was high and was traced to extraneous fringe patterns in the large HOE which become amplified in the final HOE recording.

To overcome this difficulty we decided to use a lens instead of the large HOE to from the converging beam. Large astigmatism, however, was present at the point focus after passing through the recording plate at 60^o angle of incidence. We corrected this astigmatism by introducing a second plate in the beam and tilting it around a horizontal axis until the astigmatism disappeared. This second plate was a 0.25 inch microflat glass plate. The optical system is shown in Fig. 5-5.

The final HOE's were recorded on hypersensitized Kodak 120 emulsion on 2x2 in plates. The silver halide sensitized dichromate gelatin process was used. Table 5-2 lists the steps in this process. Typical exposures were 240 seconds long and the beam ratios were in the order of 20:1. At this ratio high efficiencies cannot be achieved. To lower the

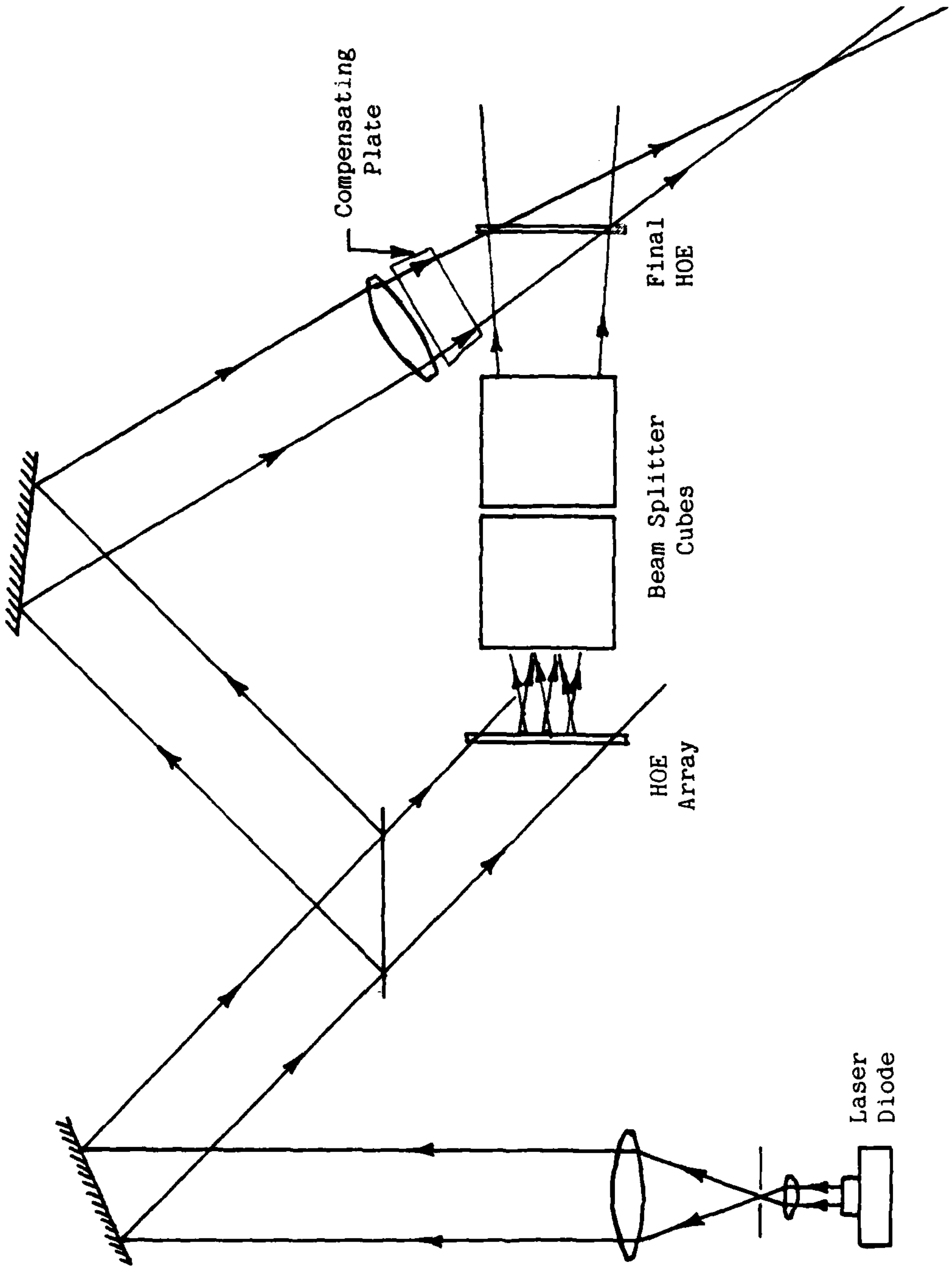


Figure 5-5. Modified optical system for recording the final HOE.

Table 5-2

Final HOE Processing

1. Develop for 6 min. in Kodak D-19 developer at 20^{o}C immediately after exposure.

2. Rinse in water for 30 sec.

3. Fix in Hunt's fixer without hardner for 5 minutes.

4. Wash for 10 minutes.

5. Rinse in Photo-Flo solution and dry at room temperature.

After plate is dry, check plate for diffraction and exposure uniformity. If acceptable, complete processing.

6. Bleach in Kodak R-10 bleach, diluted 3:1, until clear plus one minute.

7. Rinse for 15 sec. in water.

8. Fix in Hunt's fixer without hardner for 5 min.

9. Wash in running water for 10 min.

10. Soak in hot water, 90^{o} to 96^{o}C, for 20 min.

11. Dehydrate in 50%-50% water isopropanol solution for 3 min.

12. Dehydrate in 100% isopropanol for 3 min.

13. Immediately place the plate in vacuum oven at 60^{o}C and dry for 30 min. or more.

ratio much longer exposure times would be required which did not seem practical. Typical efficiencies measured with helium - neon laser were 1.5% to 3%. Fig. 5-6 shows a final HOE illuminated with incoherent light.

During the final HOE fabrication we discovered recording plate instability. This instability was traced to incomplete drying after the hypersensitization: apparently the gelatin continued to dry once removed from a storage box and mounted in a frame for exposure. The drying emulsion changed tension on the plate, causing it to bend and to move it relative to fringe position. This problem was solved by placing the storage box with hypersensitized plates in vacuum chamber for 1/2 hour or more to achieve complete drying.

Two of the best final HOE's were selected for mounting in the correlator. Cementing was done in the assembled correlator with a laser diode illuminating the HOE. With a microscope and a TV camera one of the fifteen point focii were imaged on the camera and were displayed on a TV monitor. Cement was placed between the HOE and the beam splitter cube and the HOE was carefully positioned to optimize the point focus. When the optimum position was found, the cement was illuminated with ultraviolet radiation to preharden the cement. The cube with the attached HOE was then removed and completely cured with ultraviolet light. This procedure was repeated for the second HOE.

The HOE fabrication was considerably more difficult then initially anticipated. Working with invisible radiation is also much more difficult. Observations of beam paths and alignment was possible only with hand-held IR viewers or with images detected by solid-state TV cameras and displayed on TV monitors.

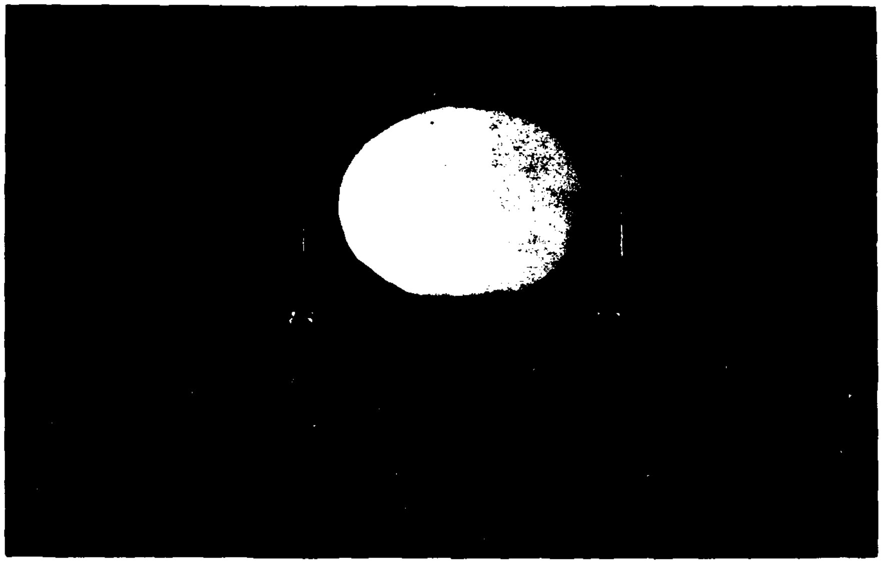


Figure 5-6. Photograph of the final HOE which contains fifteen 30mm diameter Fourier transform lenses superimposed coherently.

6.0
COMPONENT AND SYSTEM TESTS

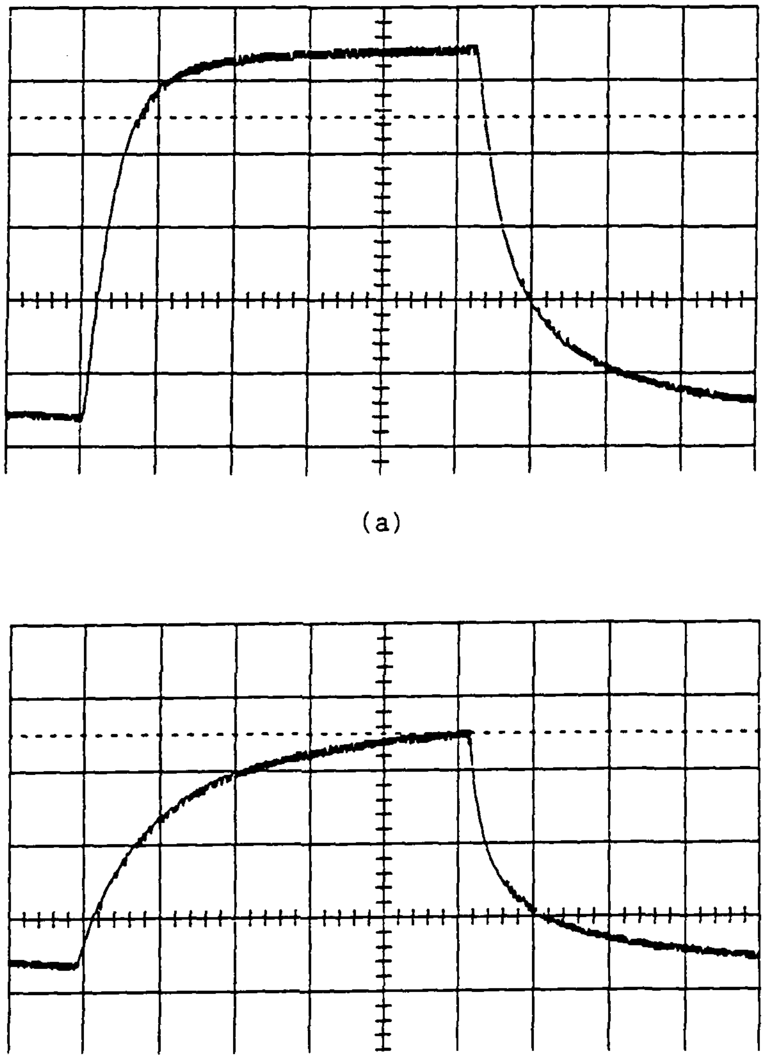
6.1 LIQUID CRYSTAL LIGHT VALVE (LCLV)

The Hughes Model H-4060 LCLVs were tested for spatial resolution, temporal response, and reflected beam flatness. The results agreed with the published specifications and were: 30 lines/mm spatial resolution, about 0.1 sec. response time when illuminated at recommended light levels, and about 1/2λ beam flatness over the central one inch diameter area. Measurements were made at the recommended bias frequency of about 10 KHz.

The LCLV was also tested with an ITT image intensifier. Due to the low brightness of the image intensifier, about 2 fL, the bias frequency had to be lowered to 1 KHz in order to obtain coherent beam modulation. This reduced the temporal response of LCLV to about 1.0 seconds. It was also observed that after prolonged complete darkness period, in excess of ten minutes, the LCLV response was much slower, requiring more than 10 seconds to reach full modulation of the coherent beam. Fig. 6-1 shows typical results both after short and long dark period.

6.2 IMAGE INTENSIFIER WITH LCLV

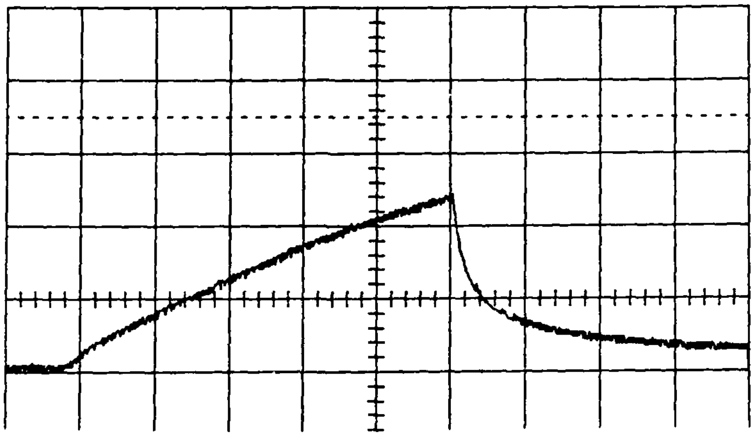
A ITT Model F-4112 microchannel image intensifier with an integral power supply was purchased. The unit was tested for resolution and output image brightness. Resolution was measured to be 8 lines/mm and output brightness 2fL. The brightness is much lower than needed to operate LCLV effectively and was lower than that reported in literature [1]. After some inquiries we discovered that 2 fL is the typical brightness for the image intensifier. On special order, modified devices can be fabricated with image brightness in the 6 to 10 fL range. The unit described in the published paper [1] apparently was a special order device.



(a)

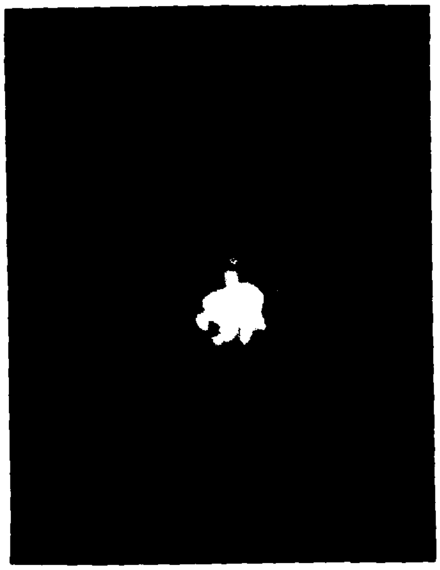
(b)

Figure 6-1. LCLV temporal response when used with image intensifier. Bias setting: 1.0 KHz at 3.56 V rms, 1.3 fL scene brightness; horizontal scale one secord per division with following lens settings: (a) f-16, after short dark period; (b) f-22, after short dark period;

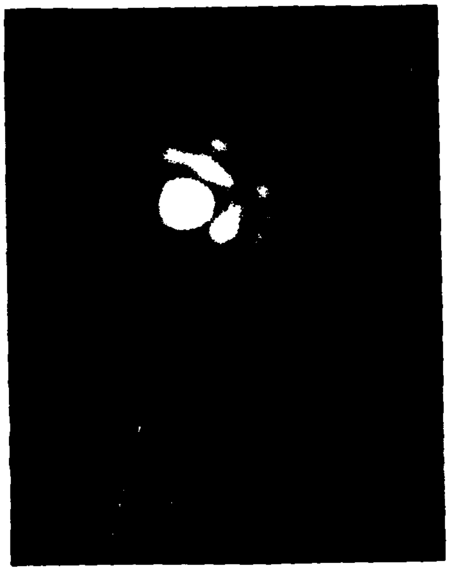


(c)

Figure 6-1. (c) f-22, after long dark period.



(a)



(a)

Figure 6-2. Photographs of point focii formed by the final two HOEs installed in the correlator: (a) from laser diode #1 and (b) from laser diode #2.

The output of the image intensifier can be coupled directly to the input of the LCLV without imaging lenses since both have fiber optics faceplates. The performance of LCLV, however, is greatly reduced by limitations of the intensifier. Combination of both units required LCLV bias adjustment to 1 KHz and 3.6 volts rms. The response time of the LCLV was about one second and resolution was about 6 lines/mm, much less than the 30 lines/mm resolution of the LCLV.

6.3 MECHANICAL FILTER HOLDER AND OPTICAL INDEXING

Filter repositioning accuracy of about $\pm$ 2μm is required in the correlator. To test filter repositioning and translating stage accuracies, an optical quadrature detector unit, UDT Model PIN-SPOT-4P, and electronic differential amplifier units, UDT Model UDT-301B-AC, were used. The quadrature detector works on the principle that light from a focused spot of light can be balanced on four detector elements. When the signals from appropriate elements of the detector are balanced, light is centered. Accuracy of this device depends upon available light level and upon the spot size. Our initial tests were performed with a 50mW focused helium-neon laser beam. The difference signals were observed on an oscilloscope where each axis of displacement was displayed along one axis of the CRT display. A scale could be established from the known motion per step of the translating stages.

A detector of this type was mounted in a metal frame as shown in Fig. 3-5. From this type of test we established that both photographic plate replacement accuracy and position repeatability was $\pm$ 0.2μm over a short period of time. Position drift after a half hour usually exceeded 10μm. The tests, however, were made on a large honeycomb steel table and did not represent positional drift with time in the correlator or the filter maker.

This type of detector mounted on steel frame was incorporated in the filter maker to establish the index point relative to which all filter positions were measured. Due to lower energy level in the focused beam and the 1 μm steps in the drive motors, an accuracy of $\pm$ 2μm was achieved in the filter maker.

Accuracy can be affected by stray light level and by beam intensity which depends upon the state of the LCLV.

6.4 CORRELATOR HOEs

The two HOEs fabricated to form the required thirty Fourier transforms were tested. A microscope was set up to image an enlarged point focus onto a solid state TV camera. Direct observation was not possible since the human eye does not have sufficient response at the laser diode wavelength of 780 μm.

Fig. 6-2 shows the spot images photographed from a TV monitor display. The spots are reasonably good although some nonuniformities exist in the diffraction pattern. The spot shape and diffraction pattern are extremely sensitive to system alignment and laser diode wavelength. The wavelength may shift if the power output or operating temperature of the diode is changed.

6.5 LASER DIODES

Laser diodes were tested for mode structure and wavelength stability by observing the interference pattern of an unequal path Michelson interferometer. The laser diode current and temperature was kept constant with the Diolite 800 controller unit. Stable fringes, over a period of several minutes, were observed with path lengths up to 150 cm. The laser diodes apparently operate in a single longitudinal and transverse mode.

During these tests we encountered erratic fringe contrast from the diodes. We traced the problem to retroreflection from the interferometer back into the laser diode. This reflection acted as a second cavity with its own mode structure. Optical systems with laser diodes must be carefully set up to prevent optical feedback into the laser diode. Otherwise, multiple mode operation may result.

6.6 CORRELATOR AND FILTER MAKER SYSTEMS

The correlator and filter maker systems were designed to operate without further manual adjustments after initial alignment. This expectation was based on the excellent replacement accuracy achieved with the filter holder and the rigidity designed into the correlator. Tests with the system showed that while rigidity designed into the correlator was adequate, filter holder repositioning accuracy was good, and automatic optical indexing system in the filter maker worked as expected, long-term alignment could not be maintained in the correlator. The apparent reason for this is misalignment caused by thermal effects on the correlator frame. Exact absolute measurements were difficult to make since a reference system is likely to undergo changes as large as those we seek to measure. Thus, we could only observe relative motion, namely those between recorded point focii on a photographic plate and the focused light spot.

The system was operated in a room typically undergoing 4^{o} to $8^{o}F$ change from morning to afternoon. We found that the correlator could be aligned on one focused spot with sufficient accuracy, and that the filter could be removed and replaced without affecting alignment. After some period of time, an hour or more, misalignment could be observed. This appears to be due to dimensional changes caused by thermal drift.

The filter maker indexing system was designed to compensate for thermal dimensional changes. Many experiments were performed in which

the indexing system performed as expected and alignment between the recorded point focus and the actual one was within specified limits. Other points on the plate, however were not necessarily in alignment. It appears that besides lateral shift in filter plate position, angular change also takes place. Since this was not anticipated, no means exist for correcting for this effect.

Operating the filter maker in an environment having more controlled temperature is probably the best solution. Placing it on top of a massive granite table having large heat capacity is also desirable.

Final tests were performed after delivery at MICOM. The environment there was more thermally stable and misalignments were much smaller. Correlations were achieved with the radial target.

7.0
FUTURE SYSTEM IMPROVEMENT

System tests revealed two primary shortcomings: insufficient long-term stability and slow temporal response. In addition, correlation spots from various filters did not coincide. The coincidence problem is a matter of alignment and can be solved by reprogramming the reference beam mirror positions.

Long-term mechanical alignment drift was evident during correlator tests. Better understanding of this problem is needed. Observations over a long period of time and under a variety of temperatures should be made. Measurements should include the magnitude and direction of misalignment, and should establish whether misalignment in only transverse or is a combination of transverse and rotational motion. It should also be determined whether the whole correlator structure or some part of it causes misalignment. For example, laser diode thermoelectric cooler generates heat and perhaps this assembly by itself may account for most of the drift. Similar observations and measurements should be made on the filter maker assembly.,

Several possible solutions exist for eliminating drift in the correlator. One is to construct the correlator frame of materials having low thermal coefficient of expansion, such as Invar. The components themselves, such as the LCLV and glass components, have different thermal expansion properties. Their interaction must be carefully considered to determine if an improvement would result.

An alternate approach is to add an active alignment system that detects alignment errors and compensates for them. The quadrature type of light detector could be located at appropriate corners of the filter array and use two out of the thirty point focii for alignment error detection. The error signal could then be used to active transducers to correct the error. The mirrors between the laser diodes and the HOEs

are easily accessible and could be tilted about two axis. Since the error is probably in the order of a few tens of microns, very slight angular mirror adjustment would suffice. Perhaps an electric magnet could apply a push or pull to an appropriately mounted mirror.

The slow temporal response of LCLV is another problem that resulted from the low light level output of the microchannel image intensifier. If the present image intensifier is replaced by a specially enhanced unit, a factor of five in brightness increase can be expected. The resulting level would still be about one-seventh of the recommended illumination level, but some improvement should result.

Another way to increase the temporal response would be to remove the image intensifier unit from the correlator. With this change low light level capability would be lost but a factor of five improvements in spatial resolution and a factor of seven to ten in temporal response would be gained. The use of the correlator, however, would be restricted to full sunlight level of illumination.

The diffraction efficiency and diffracted wave quality of HOEs could be improved. HOEs are likely to be an essential component not only of this particular but of all compact correlators. Development of better fabrication methods is needed. Diffraction efficiency in the range of 10% to 20% should be possible before intermodulation effects become significant. Beam quality could be improved by either fabricated elements on thicker and flatter substrates or by developing methods of improving surface flatness after the HOEs are mounted.

During the test and development phase of coherent correlators, means of monitoring its performance would be highly useful. Parameters that should be monitored include image brightness on LCLV or image intensifier, coherent image quality from the LCLV, and alignment accuracy at the Fourier transform plane. Image brightness could be

detected by a photosensitive detector next to the input image plane. The LCLV could be imaged onto the same detector as that which is used for correlation spot detection. A specially fabricated HOE mounted in the filter holder frame could image the LCLV onto the camera sensor.

Another improvement might be an auto-iris attachment for the image intensifier. The image intensifier life expectancy is drastically reduced if exposed to higher than specified light levels. An automatic iris control would be helpful in maintaining illuminance at acceptable levels. Off iris by itself cannot reduce light to correct levels, a shutter should close and an alarm sound to indicate incorrect bright levels.

Laser diode temperature control is very critical in maintaining wavelength stability. Initial tests indicated that short-term stability was satisfactory. Stability over longer time periods was not checked and should be investigated. Mechanical mounting of laser diode and of thermistor temperature sensor, as well as the heat sink and thermal insulation arrangements should be investigated.

Filter recording for higher diffraction efficiency also should be investigated. Efficiency depends upon beam ratios and exposure times, as well as processing. The absorbtive recording can be converted into a dielectric one by bleaching. Bleached filters have much higher diffraction efficiency. If the dielectric variations are too high, localized phase reversal in the filter can occur which degrades the correlation peak. The center of the filter should remain opaque to block the undiffracted light. Optimization and control of recording parameters and the bleaching process is needed to achieve best results.

8.0
SUMMARY AND RECOMMENDATIONS

A multiple Fourier transform compact coherent optical correlator and filter maker system was designed, fabricated, and tested. The correlator, capable of addressing 30 filter positions, was packaged into a 15cm diameter by 30cm long cylinder excluding an interchangeable imaging lens. Filters were made and correlator operation was observed. Mechanical alignment over a long period of time was found to be affected by thermal drift. An image intensifier tube with brighter output was determined to be warranted. Improvements in both of these areas are achievable.

A filter maker system was assembled for fast and reliable filter fabrication. Input to this system is in the form of a video signal. Positioning of the recording plate, the reference beam angle, and exposure times are all automatically controlled by a computer program. An optical indexing feature establishes a reference point on the recording plate to a ± 2 μm accuracy. Thirty filters can be recorded and the plate processed within 30 minutes.

The design concepts incorporated into this correlator and filter maker system represent significant advances in the practical implementation of optical correlators.

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2. H.K. Liu and J. Graeme Duthie, "Real-Time Screen-Aided Multiple-Image Optical Holographic Matched-Filter Correlator," Applied Optics 21, pp. 32787-3286, 1982.

APPENDIX A

IBM BASICA Program for Filter Maker

```
100 'FILTER PROGRAM
110 '
120 '
130 'SET-UP
140 '
150 CLS:PRINT"FILTER PROGRAM"
160 PRINT:PRINT"SET-UP"
170 DIM XP(50), YP(50), AP(50), BP(50), B%(8)
180 NFILTERS% = 30
190 '
200 'READ FILTER X,Y POSITIONS
210 FOR I=1 TO NFILTERS%
220 READ XP(I), YP(I), AP(I), BP(I)
230 NEXT I
240 '
250 'SET OUTPUT PORT TO ZERO
260 OUT &H302, 0
270 '
280 PRINT:PRINT"RESET UNIDEX CONTROLERS"
290 GOSUB 10700 'KEYPRESS PAUSE
300 PRINT:PRINT "HOMING POSITION AND ANGLES"
310 '
320 OPEN "COM1:9600,N,8,1,LF" AS #3
330 '
340 'INITIAL PARMETER VALUES
350 EXPOSURE = 5 'SECONDS
360 SETTLE = 2 'SECONDS
370 FEEDRATE% = 4000
380 TIMEOUT = 5000
390 LASER = 100
400 ACCEL% = 500
410 '
420 'SET UP UNIDEX UNITS
430 LU$ = "2"
440 FOR I=1 TO 2
450 IF I=1 THEN UNIT$ = "1"
460 IF I=2 THEN UNIT$ = "2"
470 PRINT #3, CHR$(27), UNIT$
480 PRINT #3, CHR$(27), UNIT$
490 '
500 'HOME UNIDEX
510 CS$ = "I G60=1000 G61=1000 G7"
520 GOSUB 10000 'MOTION COMMAND
530 '
540 'SET ACCELERATION AND START/STOP FEEDRATE
550 CS$ = "G37=" + STR$(ACCEL%) + "G37 G76=250"
560 GOSUB 10000 'MOTION COMMAND
570 NEXT I
580 '
590 'MAIN MENU
600 '
610 CLS:PRINT"FILTER PROGRAM MAIN MENU
620 PRINT:PRINT"    1. STAGE REFERENCE"
630 PRINT:PRINT"    2. AUTOMATIC EXPOSURE SEQUENCING"
640 PRINT:PRINT"    3. MANUAL EXPOSURE SEQUENCING"
650 PRINT:PRINT"    4. SINGLE EXPOSURE"
660 PRINT:PRINT"    5. SET PARAMETERS"
```

```
670 PRINT:PRINT"    6. END PROGRAM"
680 PRINT:PRINT
690 INPUT"ENTER SELECTION NUMBER  ",A%
700 ON A% GOSUB 1000, 2000, 2200, 2400, 5000, 720
710 GOTO 580
720 END
1000 '
1010 'STAGE REFERENCE
1020 '
1030 CLS:PRINT"STAGE REFERENCE":PRINT
1040 '
1050 XINDEX = 13640
1060 YINDEX = 14360
1070 AINDEX = 1860
1080 BINDEX = 1320
1090 '
1100 'TEST LASER POWER
1110 CHANNEL% = 2
1120 GOSUB 11100 'A/D INPUT
1130 IF ADI < LASER THEN PRINT "LASER POWER LOW":GOSUB 10700:GOTO 1100
1140 '
1150 'HOME UNIDEX UNITS
1160 UNIT$ = "1"
1170 GOSUB 12000 'SELECT UNIDEX UNIT
1180 CS$ = "I X100 F1000 Y100 F1000 G7" 'HOME POSTITON STAGES
1190 GOSUB 10000 'MOTION COMMAND
1200 UNIT$ = "2"
1210 GOSUB 12000 'SELECT UNIDEX UNIT
1220 CS$ = "I X100 F500 Y100 F500 G7" 'HOME ANGLE STAGES
1230 GOSUB 10000 'MOTION COMMAND
1240 'FIND POSITION INDEX POINT
1250 DX% = XINDEX
1260 DY% = YINDEX
1270 GOSUB 10250 'INCREMENT POSITION
1280 X = 0
1290 Y = 0
1300 '
1310 'GO TO ANGLE INDEX POINT
1320 DA% = AINDEX
1330 DB% = BINDEX
1340 GOSUB 13040 'INCREMENT ANGLES
1350 AA = 0
1360 BB = 0
1370 '
1380 'FIND X Y INDEX POINT
1390 OP1% = 1 'OPEN SHUTTER
1400 GOSUB 10400 'CONTROL REGISTER OUTPUT
1405 FOR I=1 TO 2
1410 UNIT$ = "1"
1420 GOSUB 12000 'SELECT UNIT
1430 XINCR = 1
1440 YINCR = 0
1450 SENSE = -1
1460 CHANNEL% = 0
1470 GOSUB 1600 'FIND INDEX SUBROUTINE
1480 XINCR = 0
1490 YINCR = 1
```

```
1500 SENSE = 1
1510 CHANNEL% = 1
1520 GOSUB 1600 'FIND INDEX SUBROUTINE
1530 X = 0
1540 Y = 0
1545 NEXT I
1550 GOSUB 10700 'KEYPRESS
1560 OP1% = 0 'CLOSE SHUTTER
1570 GOSUB 10400 'CONTROL REGISTER OUTPUT
1580 RETURN
1590 '
1600 'FIND INDEX SUBROUTINE
1610 '
1620 GOSUB 11100 'A/D INPUT
1630 PRINT "CHANNEL  ", CHANNEL%, " INITIAL A/D INPUT   ",ADI
1640 IF ADI > 0 THEN G = -1
1650 IF ADI < 0 THEN G = 1
1660 IF ADI = 0 THEN GOTO 1740
1670 DX% = G*XINCR*SENSE
1680 DY% = G*YINCR*SENSE
1690 CS$ = "I G91 X" + STR$(DX%) + " F10" + " Y" + STR$(DY%) + " F10"
1700 GOSUB 10000 'MOTION COMMAND
1705 IF I=2 THEN FOR J=1 TO 500:NEXT J
1710 GOSUB 11100 'A/D INPUT
1720 PRINT "CHANNEL  ",CHANNEL%, "   A/D INPUT   ", ADI
1730 IF ADI*G < 0 THEN GOTO 1690
1740 RETURN
2000 '
2010 'AUTO SEQUENCE SUBROUTINE
2020 '
2030 AMFLAG$ = "A"
2040 CLS:PRINT"AUTOMATIC EXPOSURE SEQUENCE"
2050 PRINT
2060 GOSUB 2610 'GET FILTER NUMBERS
2070 GOSUB 2830 'EXPOSURE SEQUENCE
2080 RETURN
2090 '
2100 '
2110 '
2120 '
2130 '
2140 '
2150 '
2160 '
2170 '
2180 '
2190 '
2200 'MANUAL SEQUENCE SUBROUTINE
2210 '
2220 AMFLAG$ = "M"
2230 CLS:PRINT"MANUAL EXPOSURE SEQUENCE"
2240 PRINT
2250 GOSUB 2610 'GET FILTER NUMBERS
2260 GOSUB 2830 'EXPOSURE SEQUENCE
2270 RETURN
2280 '
2290 '
```

```
2300 '
2310 '
2320 '
2330 '
2340 '
2350 '
2360 '
2370 '
2380 '
2390 '
2400 'SINGLE EXPOSURE SUBROUTINE
2410 '
2420 AMFLAG$ = "M"
2430 CLS:PRINT"SINGLE EXPOSURE"
2440 PRINT
2450 INPUT"ENTER FILTER NUMBER ",FIRST%
2460 IF FIRST% < 1 THEN PRINT"TOO SMALL ":GOTO 2440
2470 IF FIRST% > NFILTERS% THEN PRINT"TOO LARGE ": GOTO 2440
2480 LAST% = FIRST%
2490 GOSUB 2830 'EXPOSURE SEQUENCE
2500 RETURN
2510 '
2520 '
2530 '
2540 '
2550 '
2560 '
2570 '
2580 '
2590 '
2600 '
2610 'GET FILTER NUMBERS SUBROUTINE
2620 '
2630 PRINT
2640 INPUT"ENTER FIRST FILTER NUMBER ", FIRST%
2650 IF FIRST% < 1 THEN PRINT"TOO SMALL ":GOTO 2630
2660 IF FIRST% > NFILTERS% THEN PRINT"TOO LARGE ":GOTO 2630
2670 PRINT
2680 INPUT"ENTER LAST FILTER NUMBER ", LAST%
2690 IF FIRST% < 0 THEN PRINT"TOO SMALL ":GOTO 2670
2700 IF LAST% > NFILTERS% THEN PRINT"TOO LARGE ": GOTO 2670
2710 IF FIRST% > LAST% THEN PRINT"FIRST GREATER THAN LAST ": GOTO 2630
2720 RETURN
2730 '
2740 '
2750 '
2760 '
2770 '
2780 '
2790 '
2800 '
2810 '
2820 '
2830 'EXPOSURE SEQUENCE SUBROUTINE
2840 '
2850 CLS:PRINT"START OF EXPOSURE SEQUENCE  ":PRINT
2860 '
```

```
2870 'TEST LASER POWER
2880 CHANNEL% = 2
2890 GOSUB 11100 'A/D INPUT
2900 IF ADI < LASER THEN PRINT"LASER POWER LOW": GOSUB 10700: GOTO 2870
2910 '
2920 'TEST SHUTTER OPEN
2930 GOSUB 10500 'READ INPUT LINES
2940 IF IP1% = 1 THEN PRINT"SHUTTER OPEN": GOSUB 10700: GOTO 2930
2950 '
2960 IF AMFLAG$ <> "A" THEN 3000
2970 PRINT:PRINT"PREPARE INPUT IMAGE UNIT FOR AUTOMATIC OPERATION "
2980 GOSUB 10700 'KEYPRESS PAUSE
2990 '
3000 'EXPOSURE SEQUENCE LOOP
3010 '
3020 FOR I1 = FIRST% TO LAST%
3030 '
3040 XC = XP(I1)
3050 YC = YP(I1)
3060 GOSUB 10200 'GO TO POSITION
3070 AC = AP(I1)
3080 BC = BP(I1)
3090 GOSUB 13000 'SET ANGLES
3100 '
3110 PRINT USING "FILTER NO ###     X = #####     Y = #####"; I1, X, Y;
3120 PRINT USING "     A = #####     B = #####"; AA, BB
3130 '
3140 GOSUB 10800 'SETTLE TIME DELAY
3150 '
3160 IF AMFLAG$ = "M" THEN PRINT"PREPARE INPUT IMAGE ": GOSUB 10700
3170 '
3180 GOSUB 10900 'EXPOSE FILTER
3190 '
3200 'TEST FOR BREAK
3210 A$ = INKEY$
3220 IF A$ = "" THEN 3280
3230 PRINT:PRINT"SEQUENCE ABORTED"
3240 PRINT:PRINT"LAST FILTER EXPOSED WAS # ", I1
3250 GOSUB 10700 'KEYPRESS PAUSE
3260 RETURN
3270 '
3280 'ADVANCE INPUT IMAGE UNIT
3290 OP2% = 1 'SET IMAGE INPUT CONTROL LINE TO 1"
3300 GOSUB 10400 'CONTROL REGISTER OUTPUT
3310 FOR J = 1 TO 100 'PULSE LENGTH DELAY
3320 NEXT J
3330 OP2% = 0 'SET IMAGE INPUT CONTROL LINE TO 0"
3340 GOSUB 10400 'CONTROL REGISTER OUTPUT
3350 'TEST FOR INPUT IMAGE UNIT ADVANCE COMPLETED
3360 GOSUB 10500 'READ INPUT LINES
3370 IF IP2% = 0 THEN 3350
3380 '
3390 NEXT I1
3400 '
3410 PRINT:PRINT"SEQUENCE COMPLETED"
3420 GOSUB 10700 'KEYPRESS PAUSE
3430 RETURN
```

```
3440 '
5000 '
5010 'SET PARAMETERS SUBROUTINE
5020 '
5030 CLS:PRINT"PARAMETERS
5040 PRINT:PRINT"    1. EXPOSURE TIME (SEC)" TAB(45) EXPOSURE
5050 PRINT:PRINT"    2. SETTLE TIME (SEC)" TAB(45) SETTLE
5060 PRINT:PRINT"    3. FEEDRATE" TAB(45) FEEDRATE%
5070 PRINT:PRINT"    4. TIMEOUT COUNT" TAB(45) TIMEOUT
5080 PRINT:PRINT"    5. LASER POWER THRESHOLD" TAB(45) LASER
5090 PRINT:PRINT"    6. RETURN TO MAIN MENU"
5100 PRINT:PRINT
5110 INPUT"ENTER PARAMETER NUMBER  ", A%
5120 ON A% GOTO 5140, 5160, 5180, 5200, 5220, 5240
5130 GOTO 5030
5140 INPUT"ENTER EXPOSURE TIME (SEC) ", EXPOSURE
5150 GOTO 5030
5160 INPUT"ENTER SETTLE TIME (SEC) ", SETTLE
5170 GOTO 5030
5180 INPUT"ENTER FEEDRATE (INCREMENTS/SEC) ", FEEDRATE%
5190 GOTO 5030
5200 INPUT"ENTER TIMEOUT COUNT (NOMINALLY 5000) ", TIMEOUT
5210 GOTO 5030
5220 INPUT"ENTER LASER POWER THRESHOLD ", LASER
5230 GOTO 5030
5240 RETURN
10000 '
10010 'MOTION COMMAND SUBROUTINE
10020 '
10030 K = TIMEOUT
10040 PRINT #3, CS$ 'ISSUE MOTION COMMAND TO UNIDEX
10050 IF INP(&H3FE) >= 128 THEN 10100 'WAIT FOR SERVICE REQUEST
10060 K = K - 1
10070 IF K > 0 THEN 10050 'TEST FOR TIME OUT
10080 PRINT"TIMEOUT ERROR - UNIDEX"
10090 PRINT:INPUT"PRESS RETURN TO CONTINUE (AFTER UNIDEX STOPS) ",C$
10100 PRINT #3, "Q" 'QUERY UNIDEX
10110 IF INP(&H3FE) >= 128 THEN 10110 'WAIT FOR SERVICE REQUEST
10120 RETURN
10130 '
10140 '
10150 '
10160 '
10170 '
10180 '
10190 '
10200 'GO TO POSITION SUBROUTINE
10210 '
10220 DX% = XC - X
10230 DY% = YC - Y
10240 '
10250 'INCREMENT POSITION ENTRY
10252 UNIT$ = "1"
10254 GOSUB 12000 'SELECT UNIT # 1
10256 '
10260 IF ABS(DX%) < 10 THEN XFEED% = 100
10262 IF ABS(DX%) >= 10 THEN XFEED% = FEEDRATE%
```

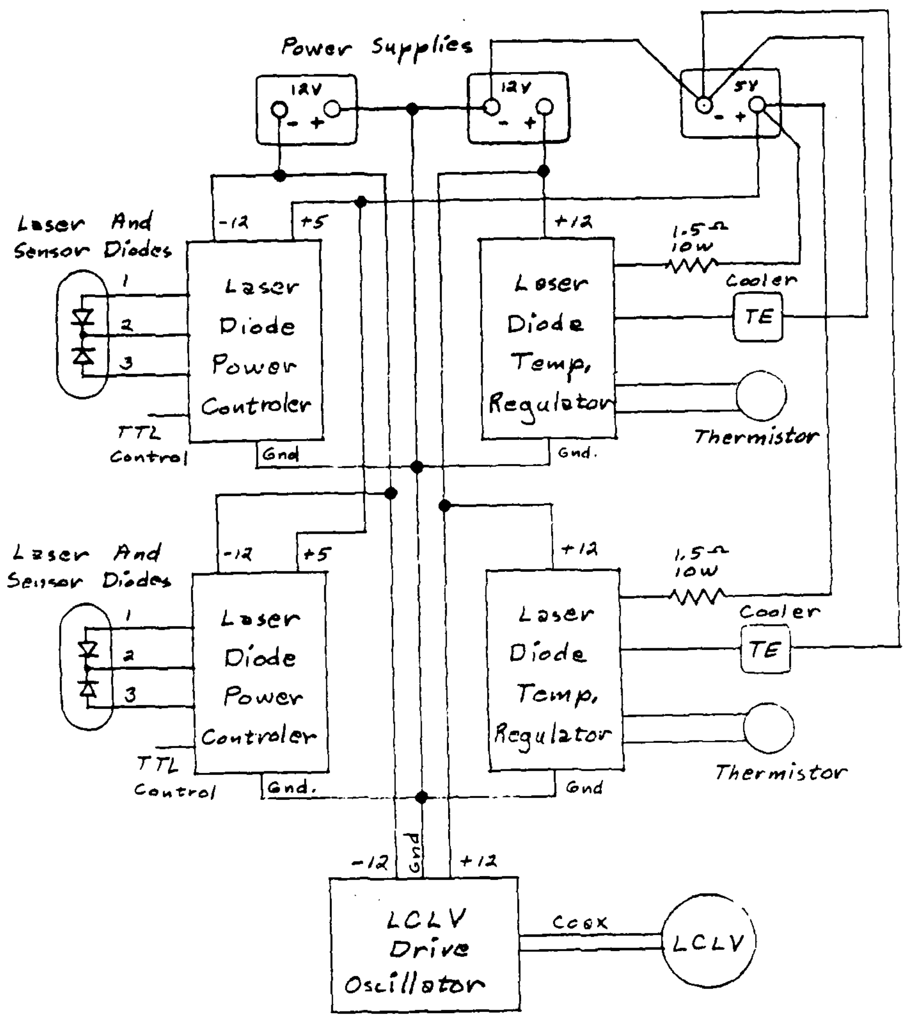
```
10264 IF ABS(DY%) < 10 THEN YFEED% = 100
10266 IF ABS(DY%) >= 10 THEN YFEED% = FEEDRATE%
10268 XCOM$ = " X" + STR$(DX%)
10270 XFCOM$ = " F" + STR$(XFEED%)
10280 YCOM$ = " Y" + STR$(DY%)
10290 YFCOM$ = " F" + STR$(YFEED%)
10300 CS$ = "I G91" + XCOM$ + XFCOM$ + YCOM$ + YFCOM$
10310 GOSUB 10000 'MOTION COMMAND
10320 X = X + DX%
10330 Y = Y + DY%
10340 RETURN
10350 '
10360 '
10370 '
10380 '
10390 '
10400 'CONTROL REGISTER OUTPUT SUBROUTINE
10410 '
10420 CONTROLREG% = CHANNEL% + 16*OP1% + 32*OP2% + 64*OP3% + 128*OP4%
10430 OUT &H302, CONTROLREG%
10440 RETURN
10450 '
10460 '
10470 '
10480 '
10490 '
10500 'READ INPUT LINES SUBROUTINE
10510 '
10520 A = INP(&H302) 'READ STATUS REGISTER
10530 FOR I=1 TO 8
10540 AI = INT(A/2)
10550 B%(I) = 2*(A/2 - AI)
10560 A = AI
10570 NEXT I
10580 IP1% = B%(5)
10590 IP2% = B%(6)
10600 IP3% = B%(7)
10610 EOC% = B%(8)
10620 RETURN
10630 '
10640 '
10650 '
10660 '
10670 '
10680 '
10690 '
10700 'KEYPRESS SUBROUTINE
10710 '
10720 PRINT:PRINT"PRESS ANY KEY TO CONTINUE  "
10730 A$ = INKEY$
10740 IF A$ = "" THEN 10730
10750 RETURN
10760 '
10770 '
10780 '
10790 '
10800 'SETTLE TIME SUBROUTINE
```

```
10810 '
10820 T1 = TIMER
10830 IF (TIMER - T1) < SETTLE THEN 10830
10840 RETURN
10850 '
10860 '
10870 '
10880 '
10890 '
10900 'EXPOSE FILTER SUBROUTINE
10910 '
10920 OP1% = 1 'OPEN SHUTTER
10930 GOSUB 10400 'CONTROL REGISTER OUTPUT
10940 T1 = TIMER
10950 IF (TIMER - T1) < EXPOSURE THEN 10950
10960 OP1% = 0 'CLOSE SHUTTER
10970 GOSUB 10400 'CONTROL REGISTER OUTPUT
10980 GOSUB 10500 'READ INPUT LINES
10990 IF IP1% = 1 THEN 10980
11000 RETURN
11010 '
11020 '
11030 '
11040 '
11050 '
11060 '
11070 '
11080 '
11090 '
11100 'A/D INPUT SUBROUTINE
11110 '
11120 GOSUB 10400 'CONTROL REGISTER OUTPUT - CHANNEL
11130 IF INP(&H302) >= 128 THEN 11130 'WAIT FOR EOC
11140 OUT &H301, 0 'START 12 BIT CONVERSION
11150 IF INP(&H302) >= 128 THEN 11150 'WAIT FOR EOC
11160 XL% = INP(&H300)
11170 XH% = INP(&H301)
11180 ADI = XH%*16 + XL%/16 - 2048
11190 RETURN
11200 '
11210 '
11220 '
12000 'SELECT UNIDEX UNIT
12010 '
12020 IF LU$ = UNIT$ THEN RETURN
12030 CS$ = " A"
12040 GOSUB 10000 'MOTION COMMAND
12050 PRINT #3, CHR$(27), UNIT$
12060 PRINT #3, CHR$(27), UNIT$
12070 CS$ = "I X0 Y0"
12080 GOSUB 10000 'MOTION COMMAND
12090 LU$ = UNIT$
12100 RETURN
12110 '
13000 'SET ANGLES
13010 '
13020 DA% = AC-AA
```

```
13030 DB% = BC-BB
13035 '
13040 'INCREMENT ANGLES ENTRY
13050 UNIT$ = "2"
13060 GOSUB 12000 'SELECT UNIT #2
13062 IF ABS(DA%) < 10 THEN AFEED% = 100
13064 IF ABS(DA%) >= 10 THEN AFEED% = 500
13066 IF ABS(DB%) < 10 THEN BFEED% = 100
13068 IF ABS(DB%) >= 10 THEN BFEED% = 500
13070 ACOM$ = " X" + STR$(DA%)
13080 AFCOM$ = " F" + STR$(AFEED%)
13090 BCOM$=" Y" + STR$(DB%)
13100 BFCOM$ = " F" + STR$(BFEED%)
13110 CS$ = "I G91" + ACOM$+AFCOM$+BCOM$+BFCOM$
13120 GOSUB 10000 ' MOTION COMMAND
13130 AA=AA+DA%
13140 BB=BB+DB%
13150 RETURN
13160 '
20000 'FILTER POSITION DATA
20010 '
20020 DATA -11075, -13472, 469, -1043
20030 DATA -5880, -13404, 246, -1038
20040 DATA -690, -13329, 23, -1032
20050 DATA 4502, -13251, -200, -1027
20060 DATA 9686, -13172, -423, -1021
20070 DATA 9616, -7990, -419, -621
20080 DATA 4433, -8062, -197, -626
20090 DATA -760, -8138, 26, -631
20100 DATA -5951, -8209, 249, -637
20110 DATA -11155, -8278, 473, -642
20120 DATA -11224, -3081, 476, -240
20130 DATA -6025, -3015, 252, -235
20140 DATA -832, -2945, 29, -229
20150 DATA 4363, -2873, -194, -225
20160 DATA 9549, -2801, -417, -220
20170 DATA 12302, 6404, -519, 497
20180 DATA 7076, 6395, -295, 497
20190 DATA 1847, 6394, -70, 497
20200 DATA -3383, 6394, 155, 497
20210 DATA -8612, 6395, 379, 497
20220 DATA -8609, 11620, 379, 901
20230 DATA -3381, 11617, 155, 901
20240 DATA 1844, 11619, -70, 901
20250 DATA 7067, 11616, -294, 901
20260 DATA 12297, 11615, -519, 901
20270 DATA 12288, 16835, -518, 1304
20280 DATA 7063, 16835, -294, 1304
20290 DATA 1840, 16839, -70, 1304
20300 DATA -3383, 16839, 155, 1304
20310 DATA -8608, 16847, 397, 1305
20320 '
```

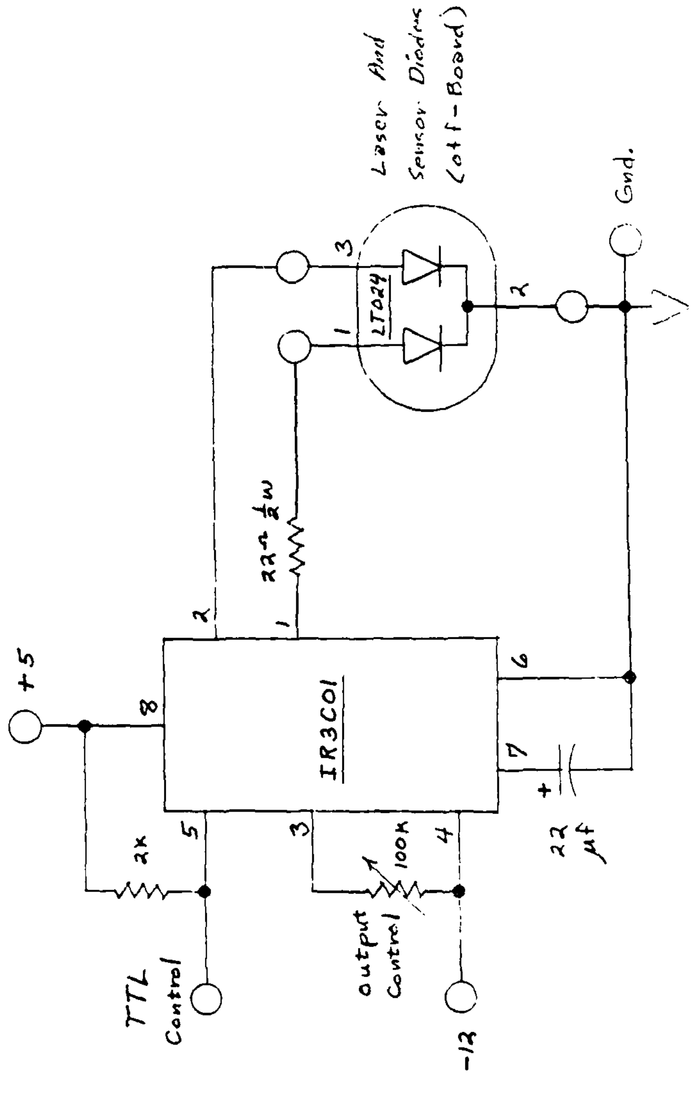
APPENDIX B

Custom-made Electronic Circuits for the Compact Correlator

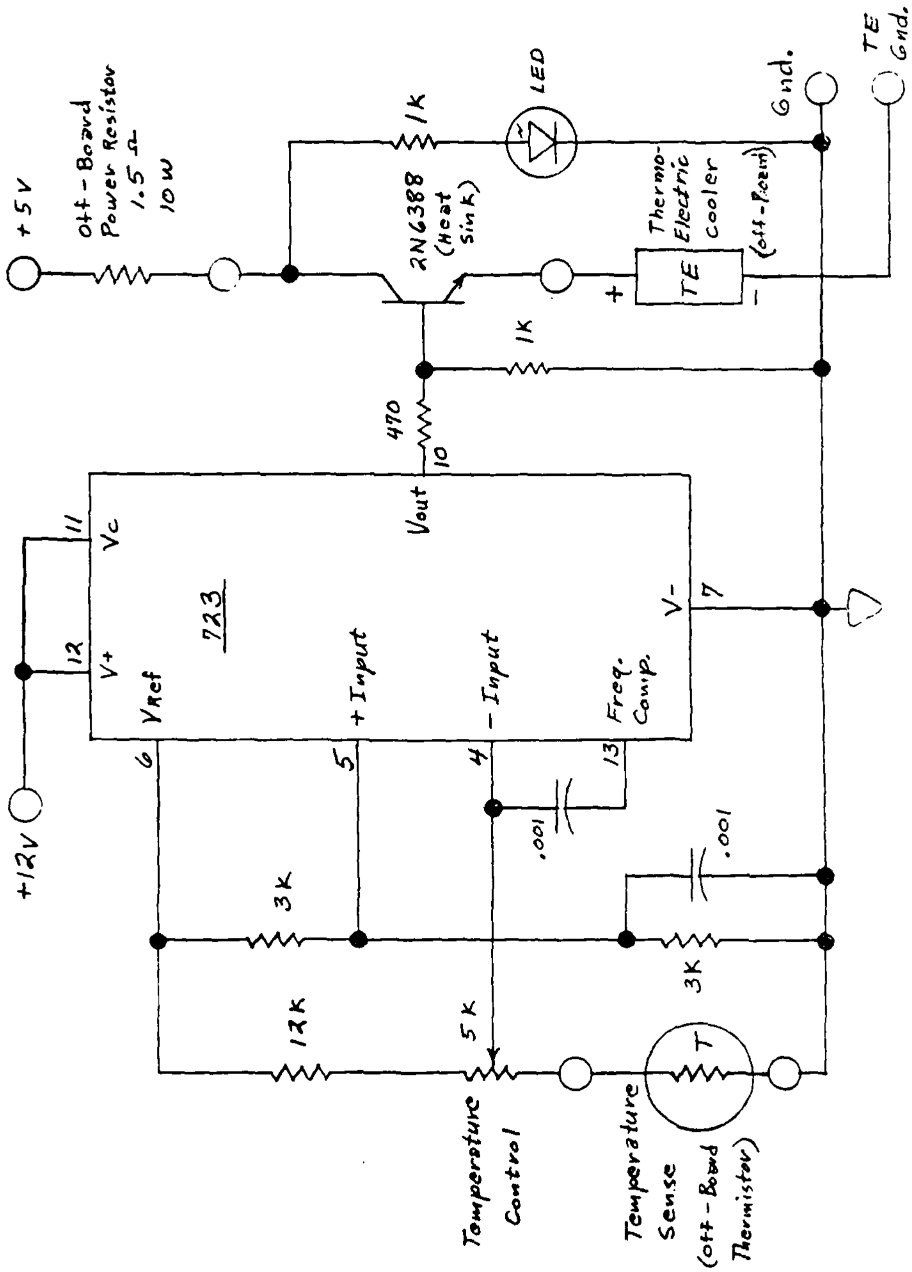


Correlator Electronics

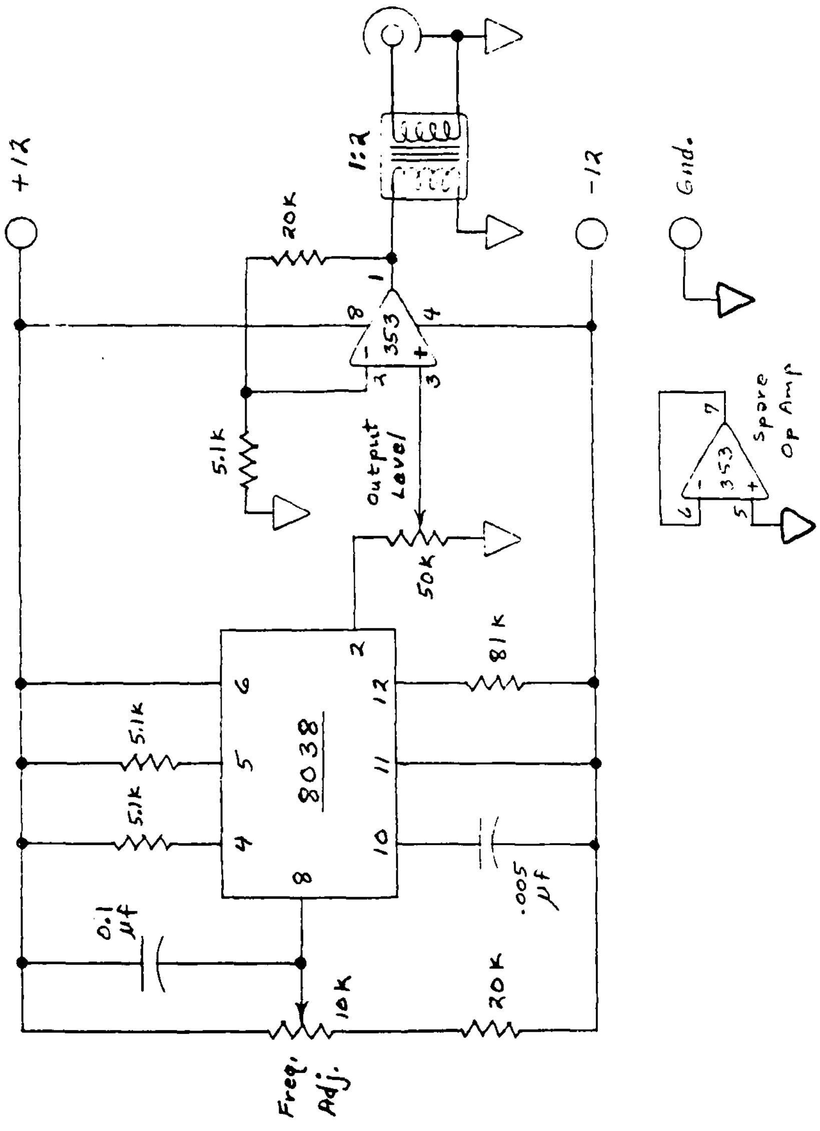
LASER DIODE POWER CONTROLER

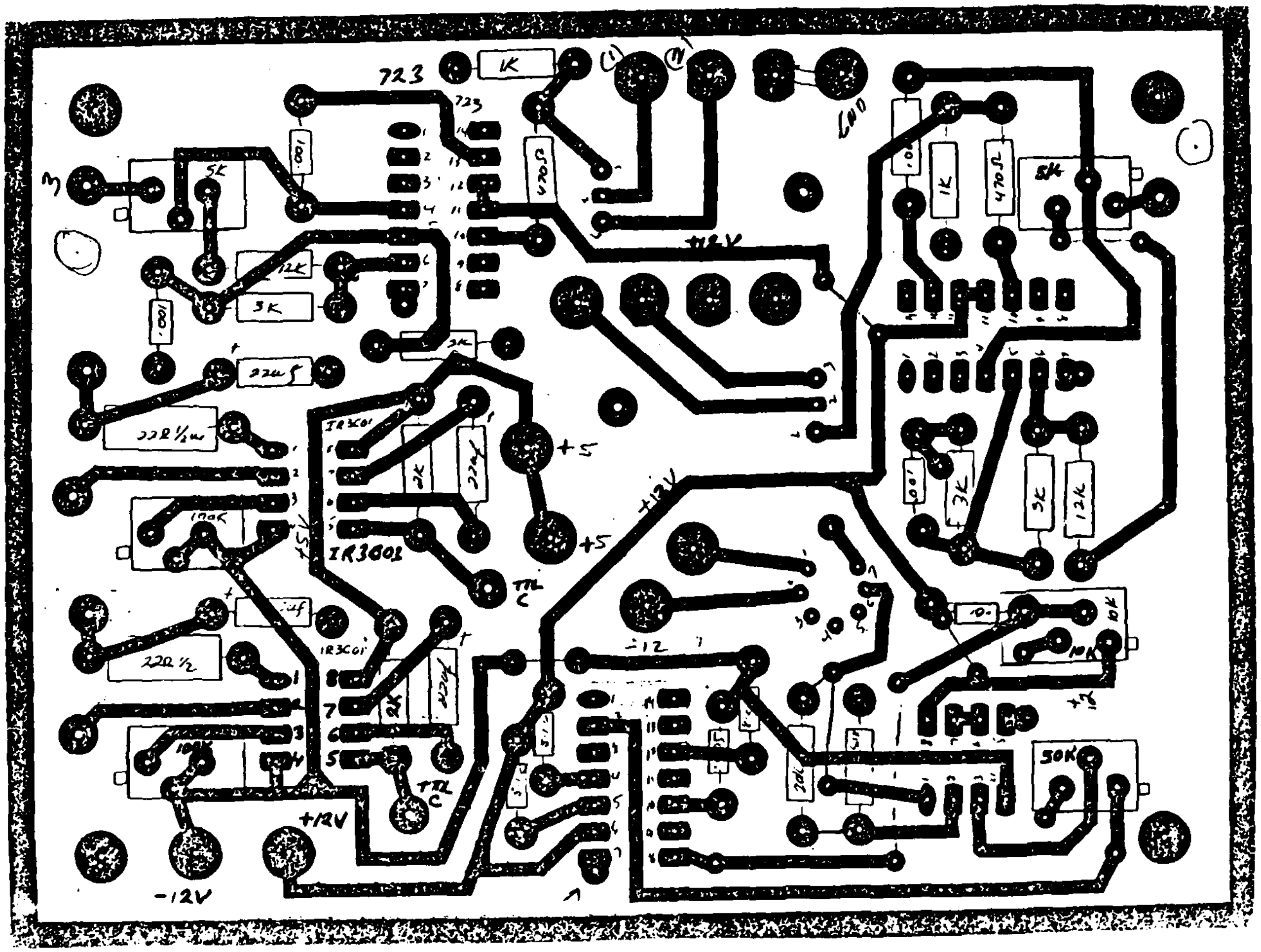


LASER DIODE TEMPERATURE REGULATOR



LCLV DRIVE OSCILLATOR





Magnified circuit board layout. This board contains two laser diode power controllers, two laser diode temperature controllers, and one LCLV driver oscillator.

APPENDIX C

List of Major or Unique Components

Description	Manufacturer
Laser diode, λ = 780nm, Model # LT024MF	Sharp
Laser diode output power controller IC, Model # IR3C01	Sharp
Laser diode system, with temperature and output control, Diolite 800-30	Liconix
High-brightness CRT display, EDP 58, Model # 38-B02405-71, with P53 green phosphor	Video Concepts
Dual 9 in. rackmounted B/W TV monitor, Model TR-932	Panasonic
Electronic shutter control unit, Model #SD-10	A.W. Vincent Assoc.
Electronic Shutter, Model #214L4A1T5	A.W. Vincent Assoc.
Quad photodetectors, Model #PIN-STOT-4D	United Detector Technology
Sum and difference amplifiers for quad photodetectors, Model #UDT-301B-AC	United Detector Technology
Laser diode output sensor, Model # 882 Photosensor	Newport
Zero order half-wave plate Model # 8-8015-1/2-780	Special Optics
Polarizing beam-splitter cube, Model #BBPC50-780	Karl Lambrecht
Linear positioning stage, Model # ATS302MM/65SMW/SM-0	Aerotech
Rotary positioning stage Model # ART304(.5)/65 SMW/SM-0	Aeortech

Unidex Motion Control, Model IIIA, Part # UNIDEX IIIA/2C/4005/4005/W/W	Aerotech
Liquid Crystal Light Value, optimized for 780 nm wavelength, Model #H-4060	Hughes Aircraft
Microchannel Image Intensifier Model # F4112(S20/G, P31/HVFO/NESA)	ITT
Integral power supply for F4112 image intensifier, Model #2082	ITT
Miniature TV camera, Model #XC-37	Sony
Ultraminiature transformer for LCLV bias circuit, Model #Y-27375	Pico Electronics
Triple output power supply, +5V, +/-12V, Model #3V51212T9A	Acopian Corp.
Laser diode anamorphic prism pair, Model #06GPA004	Melles Griot
IBM PC with 256K memory, 2 floppy disc drive units, monochrome IBM adapter, RS-232 interface card and PC-DOS 2.1	IBM
Video monitor, Model 310A	Amdek
8-channel A/D converter card for IBM PC, Model DASH-8	Metra Byte
Screw termination board Model STA-08	Metra Byte